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CAMPUS DE EXCELENCIA INTERNACIONAL

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La Palma Interferometer: objetivos científicos

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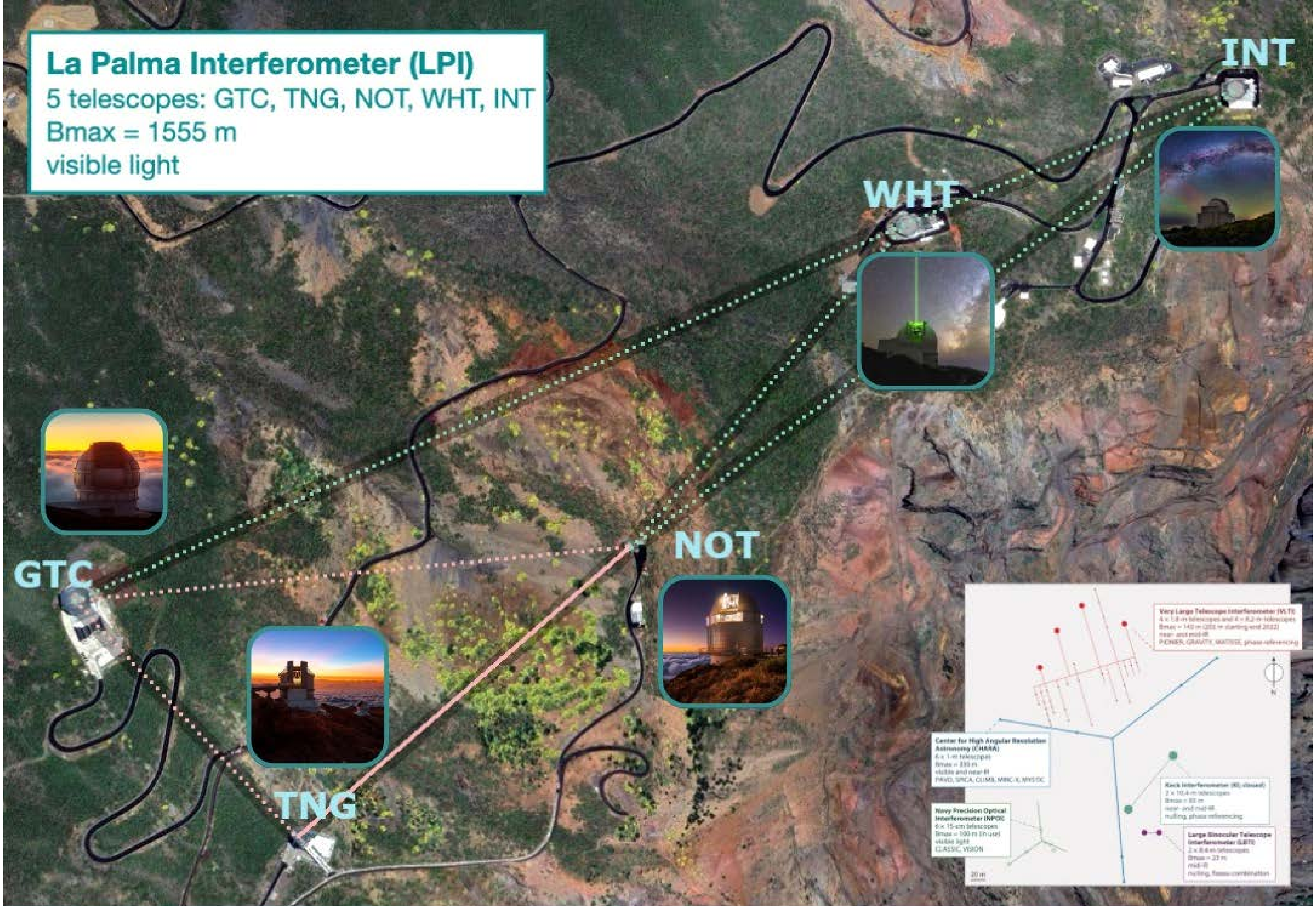
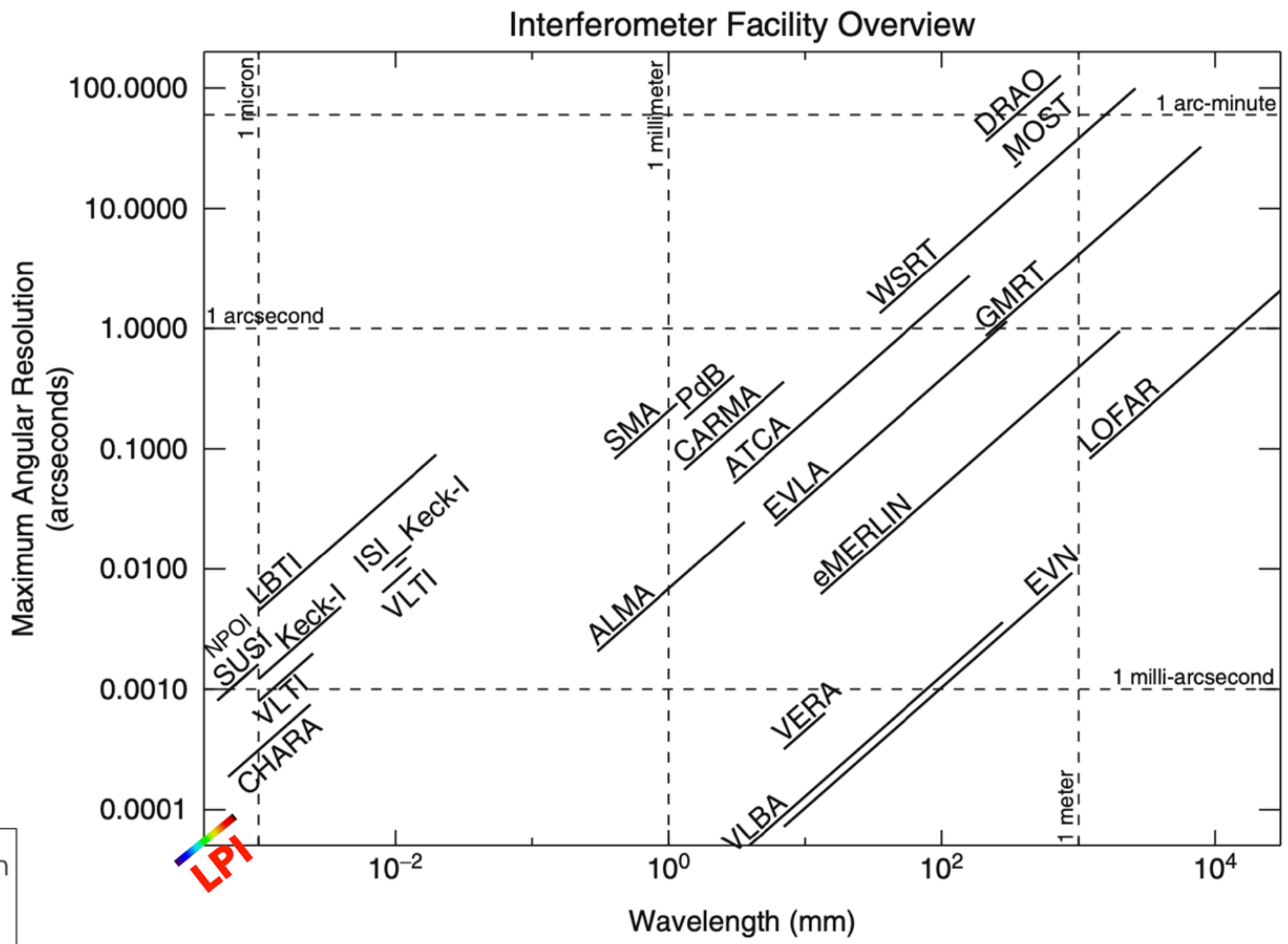

La Palma Interferometer (LPI)
5 telescopes: GTC, TNG, NOT, WHT, INT
Bmax = 1555 m
visible light
INT
WHT
GTC
NOT
TNG



LPI 1555m @ 450nm

$\lambda/D = 60\ \mu as$

Fig. 7-14

Graphical representation of the wavelength coverage and maximum angular resolution available using the radio and optical interferometers of the world.

Monnier & Allen review

LPI: Física de eventos transitorios de duración ultracorta

Algunos eventos de interés astrofísico que ocurren en entornos o fuentes de variabilidad ultra-rápida son :

- Milli-second pulsars
- Fast Radio Bursts (FRB)
- Short Gamma Ray Burts (GRB)
- Kilonovae (KN) o coalescencia NS
- Detección de exoplanetas
- Disco acreción BH

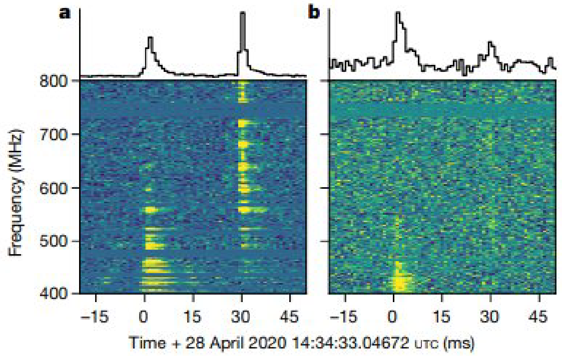
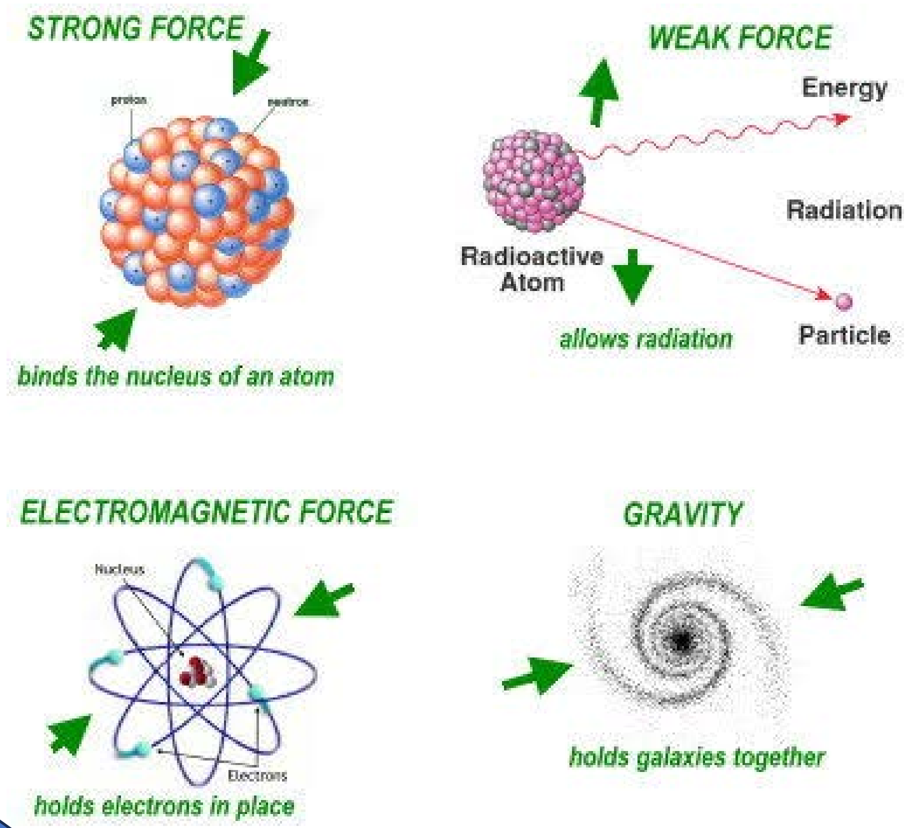


Fig. 1 | Burst waterfalls. a, b, Total intensity normalized dynamic spectra and band-averaged time-series (400.1953125-MHz arrival time referenced to the geocentre) of the detections by CHIME/FRB (**a**) and ARO (**b**), relative to the geocentric best-fit arrival time of the first sub-burst based on CHIME/FRB data For CHIME/FRB, the beam detection with the highest signal-to-noise ratio, *S/N*, is shown. Dynamic spectra are displayed at 0.98304-ms and 1.5625-MHz resolution, with intensity values capped at the 1st and 99th percentiles. Frequency channels masked owing to radio-frequency interference are replaced with the median value of the off-burst region. The CHIME/FRB bursts show a 'comb-like' spectral structure owing to their detection in a beam sidelobe as well as dispersed spectral leakage that has an instrumental origin (see Methods).

CHIME col. burst SGR 1935+2154



en ellos se pone de manifiesto la física extrema:
intensos campos gravitatorios que crean densidades extremas y emiten grandes cantidades de energía en eventos transitorios

$$\tau_{\rm dyn} \sim \frac{R}{v}$$ es del orden 10^{-3} s

$$R \sim 10^6 - 10^7 \ \mathrm{cm}$$
$$v \sim c$$

Física Fundamental en conjunto (+exótica) explica de forma armoniosa la fenomenología subyacente y nos permitirá entender mecanismos internos con valor extra de multimensajeros: GW, neutrinos, rayos cósmicos

LPI: resolviendo estructura espacial/temporal Cygnus X1

Con las capacidades únicas de LPI seremos capaces de resolver escalas del entorno de 50 micro-arcsecond. Las tecnología ultra-rápida es capaz de resolver detalles espaciales/temporales y entender los mecanismos detrás de fuentes con alta variabilidad.

Los objetivos científicos de LPI incluyen

RX en Chandra, IXPE, XMM-Newton

Resolución de disco de acreción de **Cygnus X-1**: un sistema binario compuesto por un agujero negro (BH) 21Mo, rotando 800 Hz y una supergigante azul HDE 226868 a 7000 años luz. Descubierto en 1964.

Típicamente a esa distancia resolución espacial 17000 km

$$s \approx 6.85 \times 10^{19} \times 50 \times 10^{-6} \times \frac{\pi}{648000}$$

Hitos:

-extensión del disco de acreción de BH hasta la ISCO (innermost stable circular orbit)

-geometría y efectos Relatividad General: curvatura luz, lensing

-distribución de temperaturas en disco

-formación de jets: discernir escenarios

Timescale 10^{-3} s-1s

-variabilidad en escalas temporales: plasmas, turbulencia

LPI: llegó la hora de las estrellas ultradensas

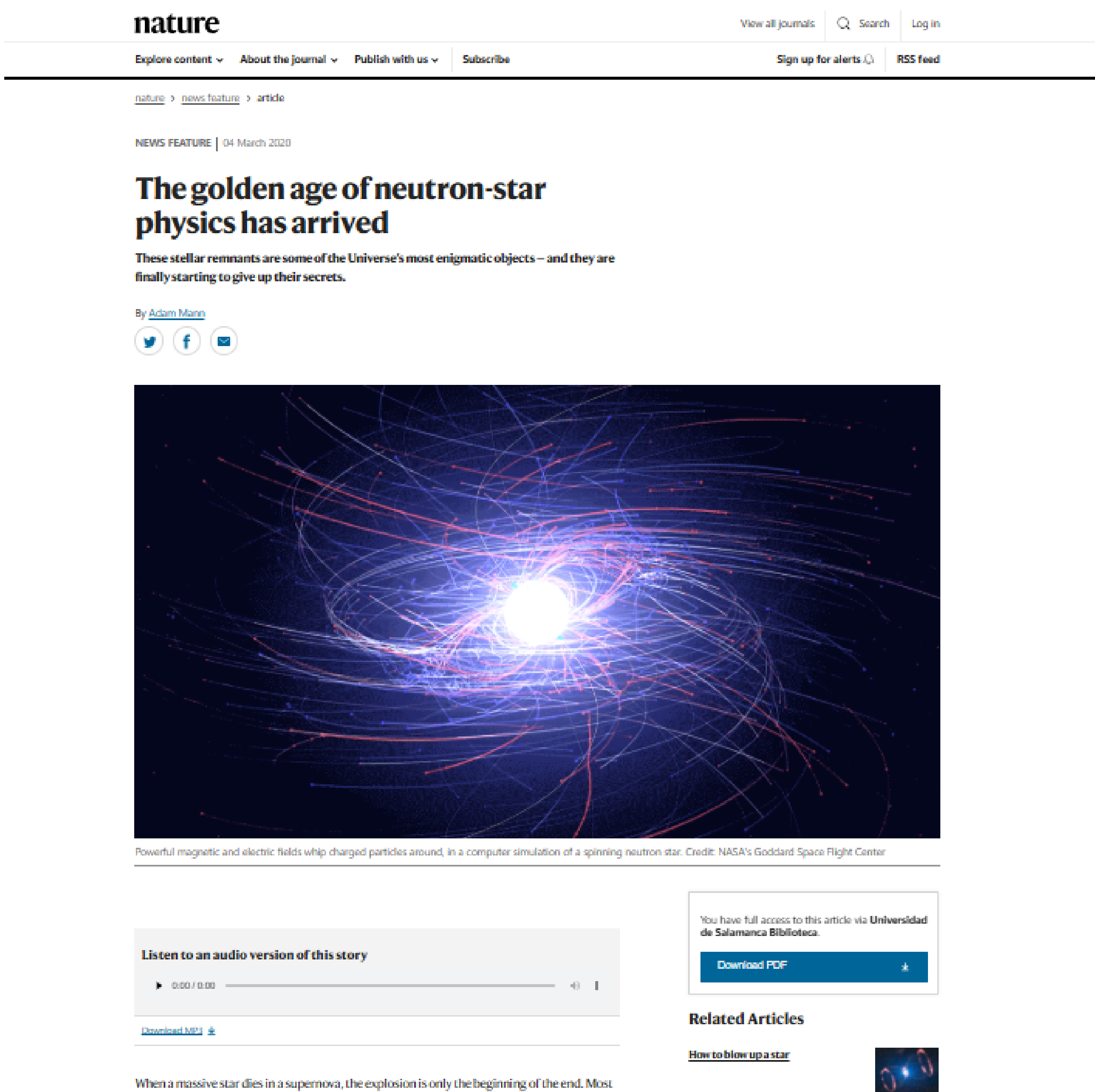
- La revista Nature en 2020 ya indicaba el inicio de una nueva era en el estudio de estos objetos.

- Su interior ultradenso, gravitacionalmente compacto, cuántico, relativista, magnetizado los hace únicos.

- Su regularidad los hace fácilmente identificables. 3000 conocidos en catálogos, mayoritariamente radio, gamma, hasta el momento detectados 6 ópticos.

- Fuente de multimensajeros en física: fotones, GW, neutrinos y rayos cósmicos acelerados en sus campos magnéticos.

- Poco después de 1964 de hallar Cygnus X1, aparecería el primer pulsar (NS rotante) en 1967, Bell+Hewish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NEWS FEATURE | 04 March 2020

The golden age of neutron-star physics has arrived

These stellar remnants are some of the Universe's most enigmatic objects – and they are finally starting to give up their secrets.

By Adam Mann

Powerful magnetic and electric fields whip charged particles around, in a computer simulation of a spinning neutron star. Credit: NASA's Goddard Space Flight Center

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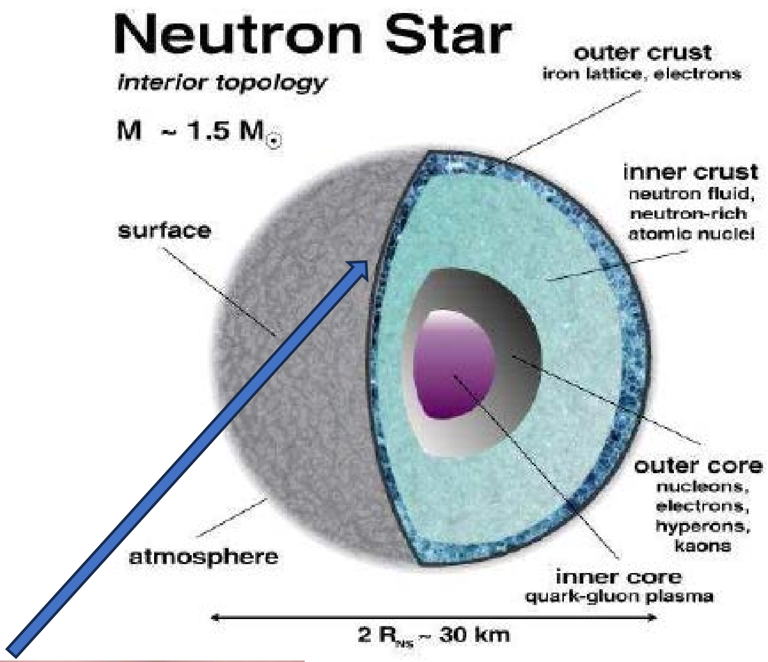
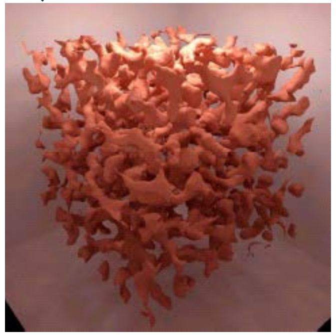
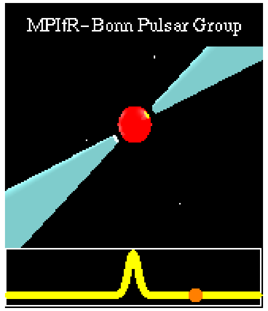
Estrellas de Neutrones





Materia de la corteza



•Después de explosion de Supernova de estrella con masa superior a 8 M_sol resulta objeto colapsado.

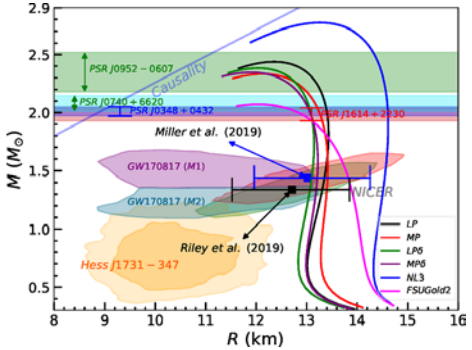
•Estructura estratificada en capas, exterior crista lino, interior fluido: n, p, electrons y otros leptones y hadrones.

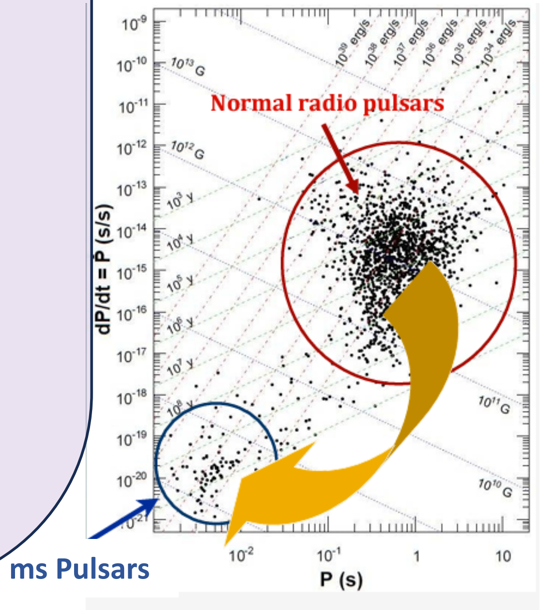
•Interior densidad superior a núcleo atómico 5-10 veces.
•Materia ultradensa y fría al cabo de días.

•Efectos campos gravitatorio 1e5 veces superior al sol. M/R~0.1 , B~10^{15} Gauss (magnetars)

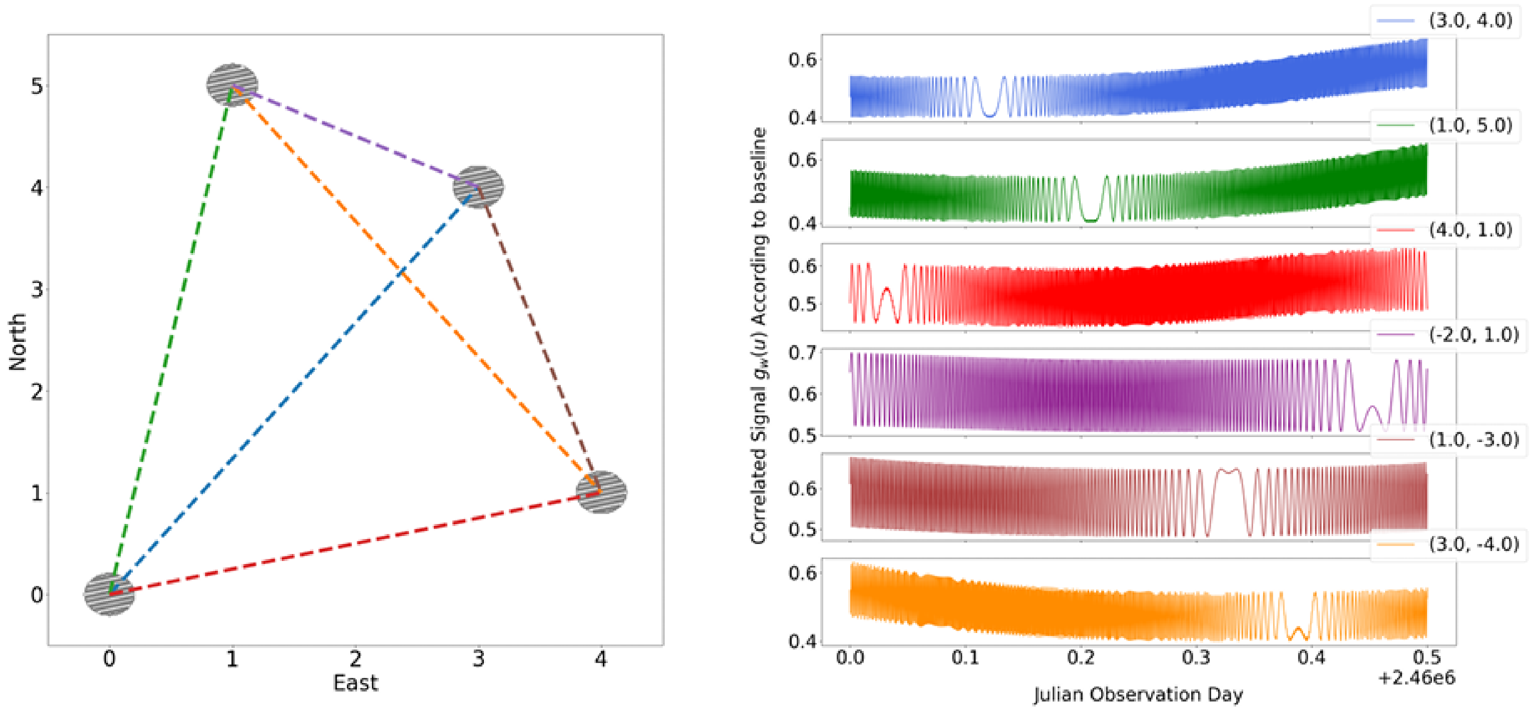
•M<2M_sol, R<15 km.

•Colisiones binarias NS, NS+BH medibles GW y luz, próxima mente neutrinos?





Detección de exoplanetas: ejemplo Alpha Centauri



(a) The position of telescopes (b) Model signal according to baselines

Figure 3. The left figure shows the position of the four telescopes ((E,N) = (0,0), (1,5), (3,4), (4,1)). The right figure shows the signal according to each baseline for one-night observation. Here the colors of baselines joining the telescope have been taken as the same colors as signals.

taken from Rai et al MNRAS 2022.

LPI ofrece la posibilidad de estudiar perturbaciones de astrometría orbital con gran precision 50 μas.

Como ejemplo, para Alpha Centauri A o B la existencia de planeta generaría perturbación astrométrica
menor de 10 μas, la cual
podría determinarse

1e-6 de separación entre las dos estrellas

resolución necesaria 0.1 ns

Kilonovas: binarias NS y su contrapartida EM

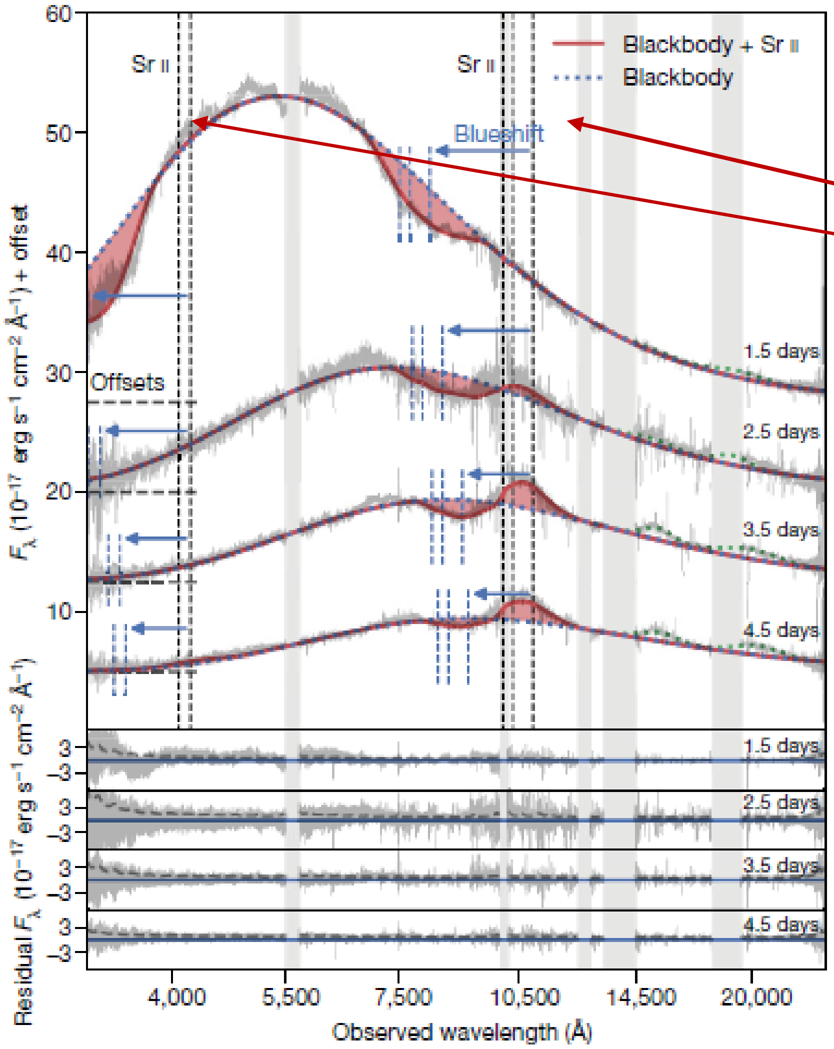
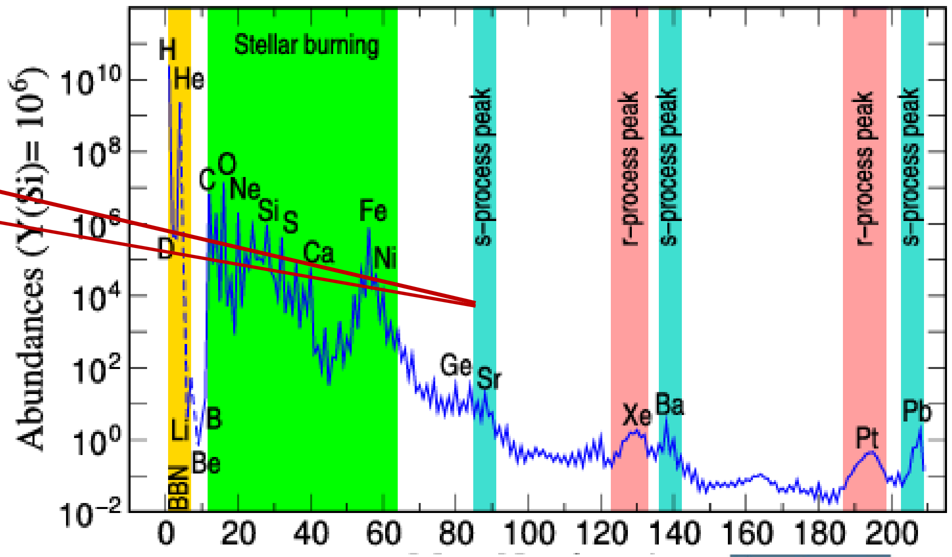
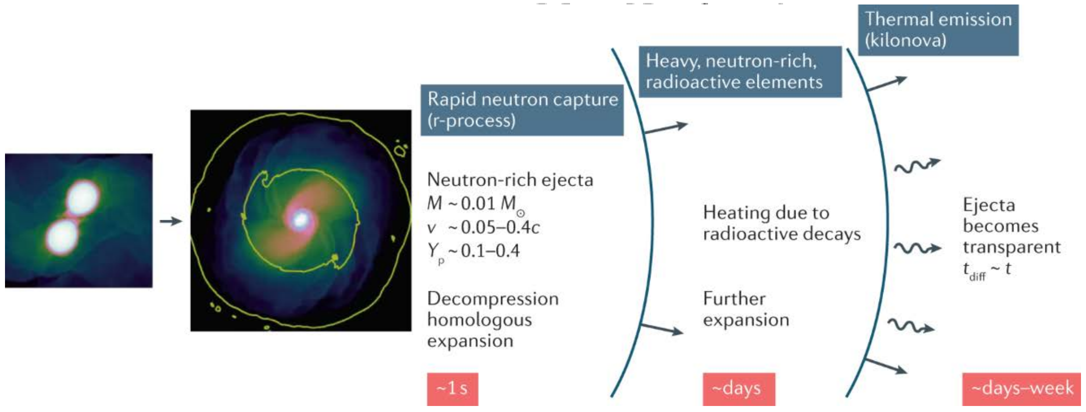


Fig. 4 | Spectral series of AT2017gfo 1.5–4.5 days after the merger. Data are

Kilonova AT2017gfoWatson et al, Nature 2019

Cowan RMP 2021.





Para elementos más pesados que el Fe, la captura rápida/lenta de n respecto a decay débil marca r-process– que luego decaen en optical-UV

Conclusiones

- La física de eventos ultrarápidos domina eventos astrofísicos de extraordinaria importancia donde los tiempos dinámicos son inferiores al milisegundo, con subestructura del rango de nanosegundos.

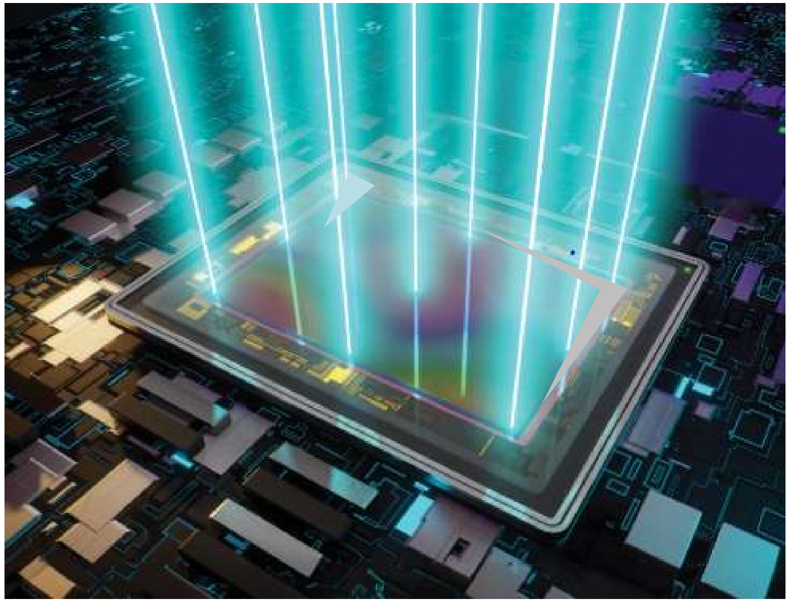
- Se ponen de manifiesto la física de lo extremo: intensidad de campos fundamentales, materia ultradensa. Hace falta nueva tecnología SPADs capaz de poder capturar esta información.

- LPI con sus capacidades únicas de resolución espaciotemporal será capaz de marcar diferencia cualitativa en la comunidad y discernir escalas antes no posibles, a través de interferometría de intensidad. LPI como telescopio único es equivalente a uno con espejo primario 15.4m permitiendo realizar espectroscopía de objetos débiles, solo posibles con GTC actualmente.

- Estudio de discos de acreción (distribución de T, plasmas, jets) alrededor de BH o emision de radiación durante FRB o very short GRBs, detección de exoplanetas serán posible. La subestructura de pulsos de tamaño ms será accesible y permitirá testar modelos sobre los mecanismos internos.

- LPI está concebida como una instalación científica de vanguardia que se ofrecerá toda la comunidad astronómica española, con sinergias en el campo de la comunicación cuántica y la geofísica (sismología).

Gracias



Contextualizing CMOS SPAD Area Sensors

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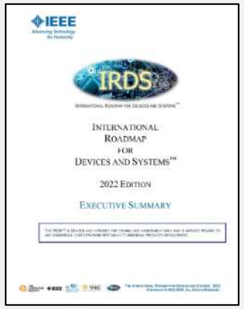
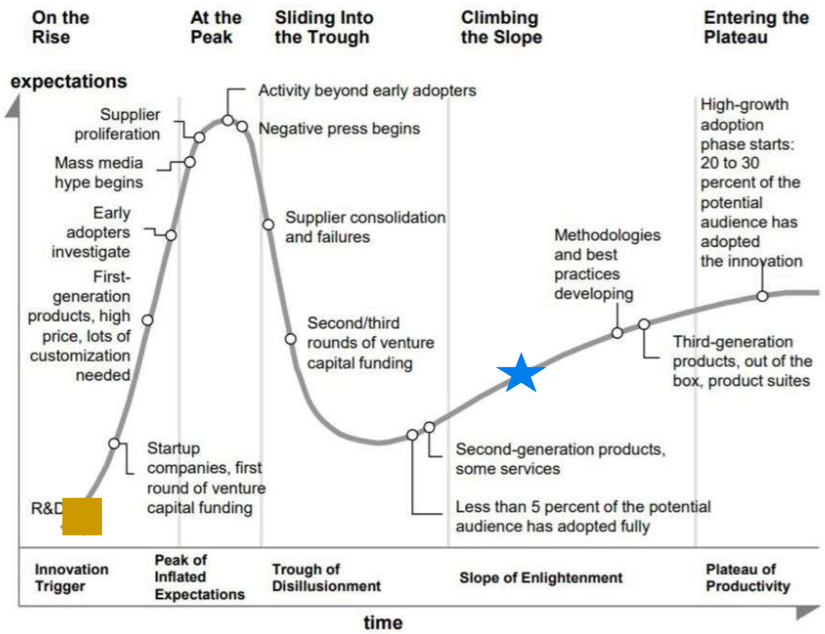
April 08, 2025

Regarding Facts and Expectations: ***Hopes for SPAD Arrays***

Strategic agendas forecast the ubiquitous deployment of miniaturized systems with vision capability

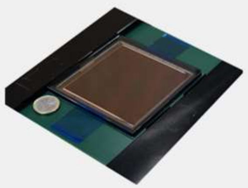


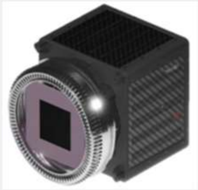


- **CISs lasted >30 years from first APS until reaching plateau of productivity**
- **Computer Vision moved very rapidly towards plateau of productivity according to Gartner data**
- **SPAD Arrays foundations has been solidly built during ~25 years**
- **3D stacked technologies are rapidly maturing and becoming available**
- **Moving to the plateau of productivity may be close for SPAD Arrays**

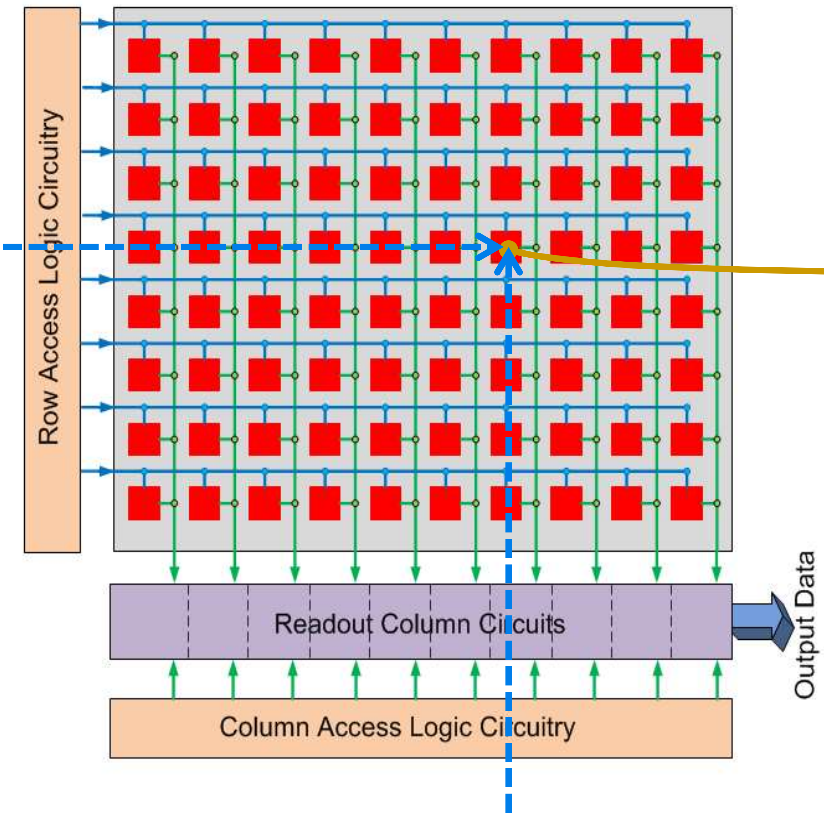
Source: (i) www.gartner.com; (ii) credit to Smashicon and Flaticon for the icons

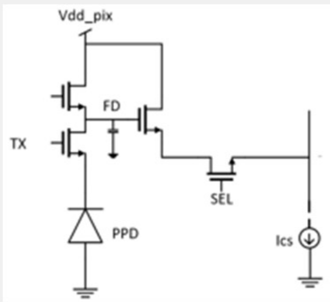
CMOS IMAGE SENSORS: Basic Architectural Concept



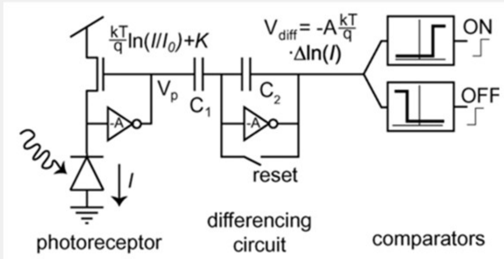


- **CIS CONCEPT:**
  - **Silicon-based CMOS chips**
  - **Used at the front-end of camera systems**
  - **Rely of photo-electric effect to transduce optical scenes into digital images (arrays of digital numbers)**
- **BASIC ARCHITECTURE:**
  - **Array of pixels, each capturing a spatial image sample**
  - **Row and Column decoders for addressing Y- and X-positions**
  - **Readout circuitry to output data**
- **MANY POSSIBLE PIXEL ARCHITECTURES/CIRCUITS !!**

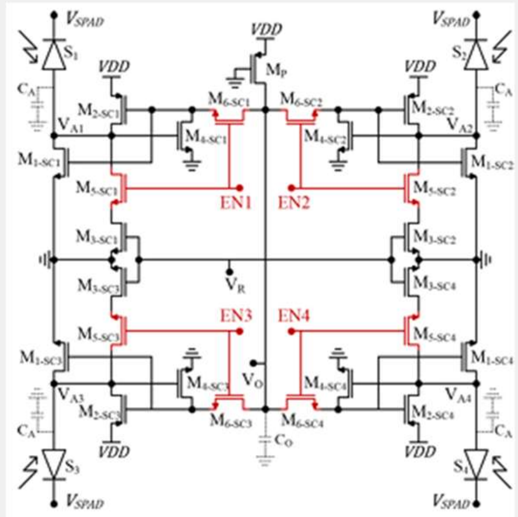




4T-APS

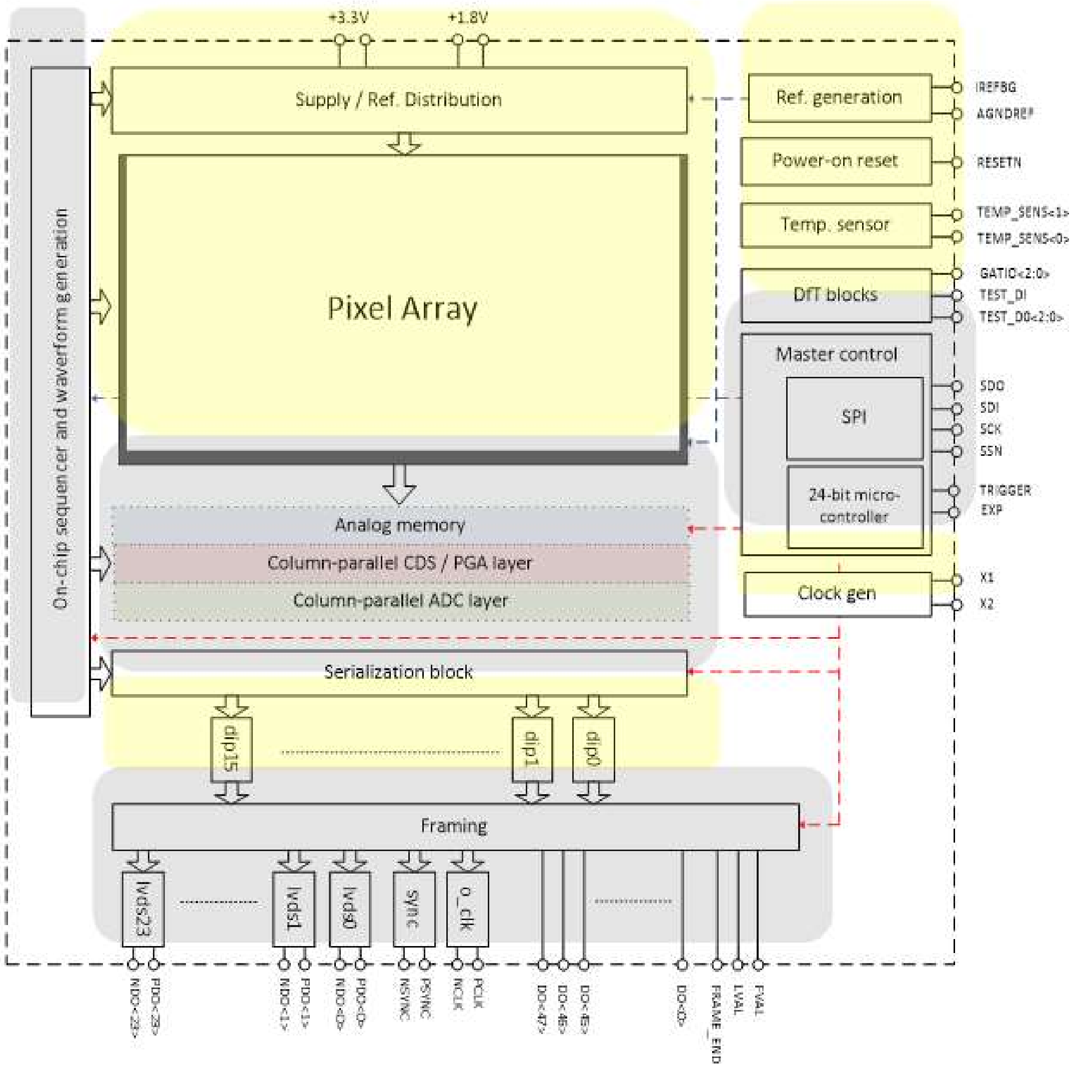


DVS Pixel



SPAD-SiPM Pixel

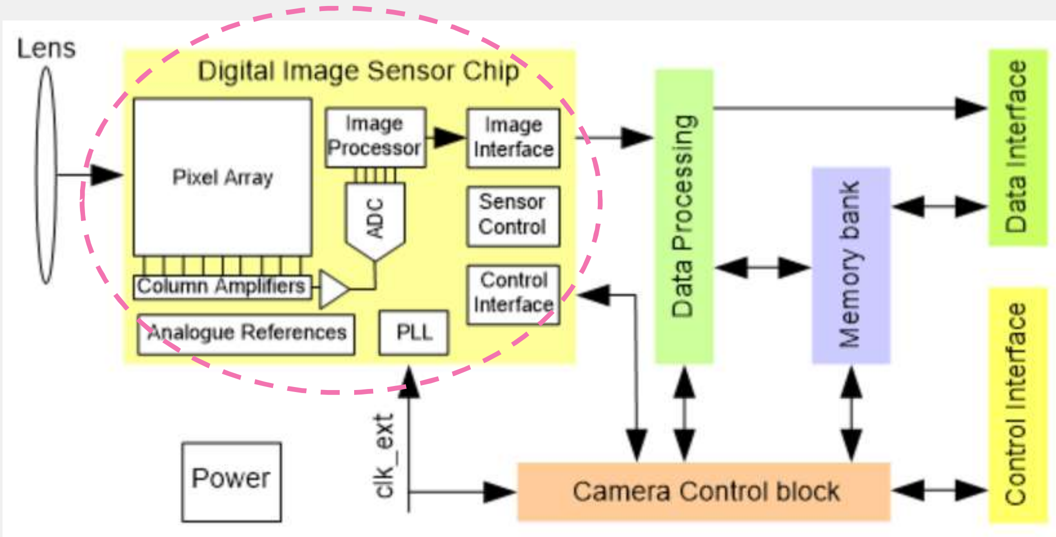
CMOS IMAGE SENSORS: *Camera-on-a-Chip Concept*



Low-noise CIS floor-plan ©TELEDYNE ANAFOCUS

CMOS TECHNOLOGIES PERMIT TO CO-INTEGRATE

- The sensor **front-end** capturing images
- Many other **functions** required for **camera systems**
  - Readout and Analog-to-Digital Conversion (ADC) channels
  - System control & programming
  - Image correction, calibration and pre-processing
  - Data communications and image interface
  - Clock generation
  - etc.

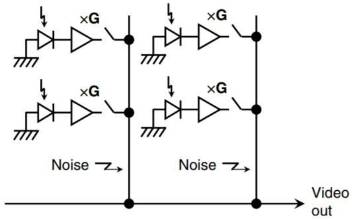


Some Representative Historical CIS Milestones

MOS Active Pixel
Array implemented

1968

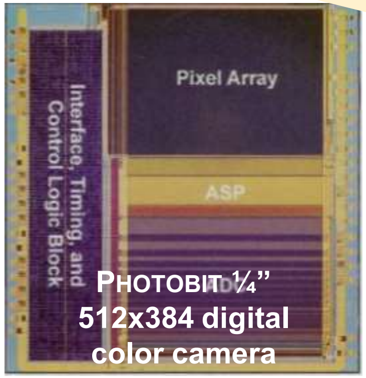
P.J.W. Noble

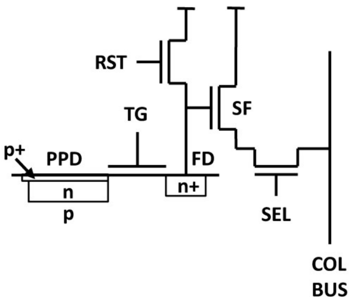


Camera-on-a-Chip
Concept Implemented

Pinned CIS Photodiode
Widely adopted

~2000

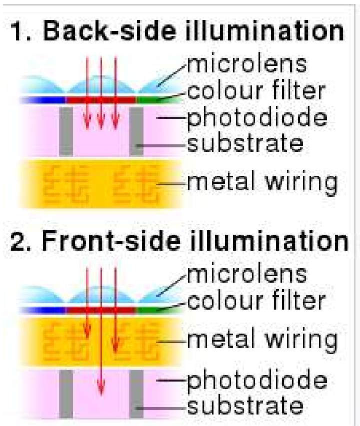




Commercial Back-side illuminated CIS

- Sony
- Omnivision
- etc.

2008

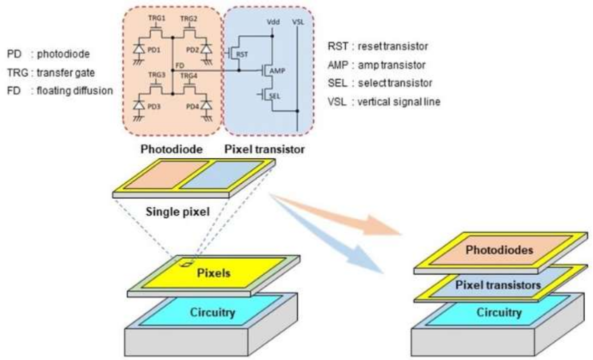


Commercial BSI Stacked CIS

SONY Exmor CMOS Sensor

Sony Exmor RS

2012



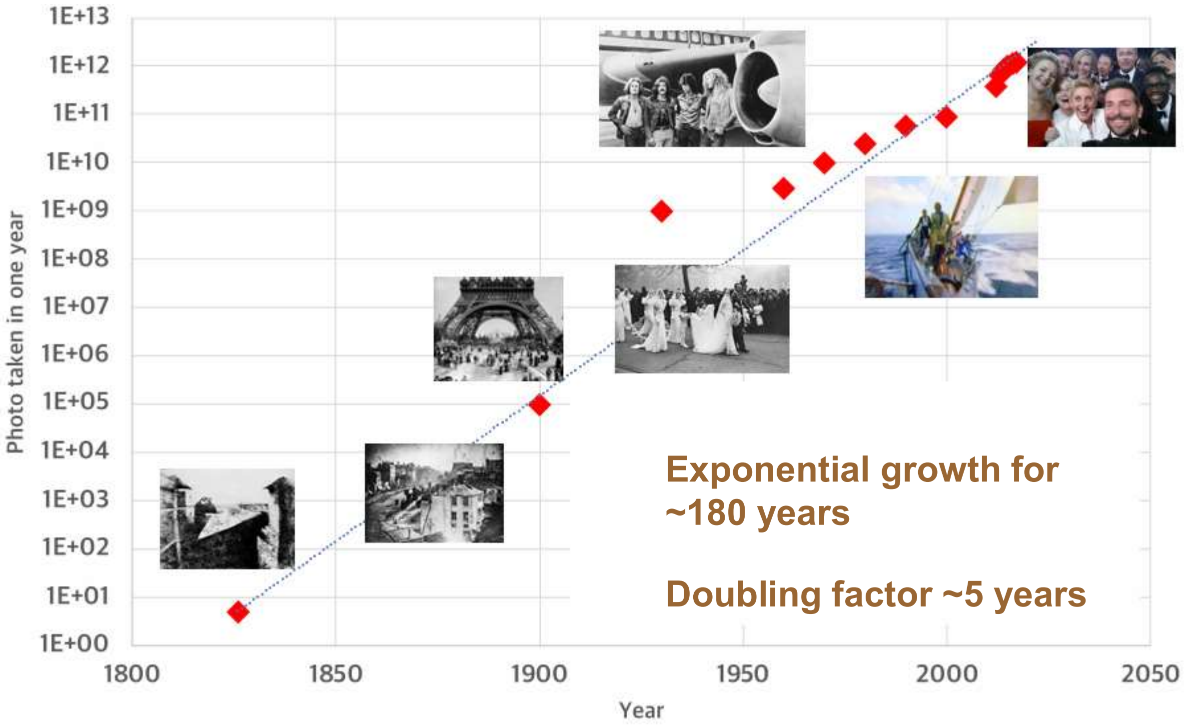
> 2020

- Readout Parallelization, BSI, Wafer Stacking

adopted by major CIS producers and fabless companies

- Range Sensors (3D scenes)
- Single Photon Detection Sensors
- Dynamic Vision Sensors
- Etc.

ON THE RELEVANCE OF CISS: *Imaging Techno Proliferation*



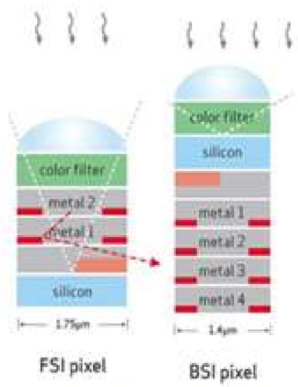
©Renato Turchetta

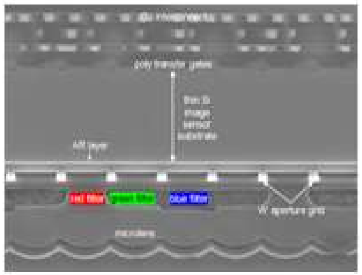
©Yole Development

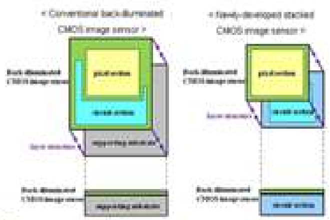
Source: R. Turchetta, "CMOS Image Sensors." *2023 BARCELONA TECHNO WEEK*.
YOLE DEVELOPMENT. https://www.yole.fr

SOME RELEVANT CIS CHALLENGES

Enlarged Granularity and Responsivity

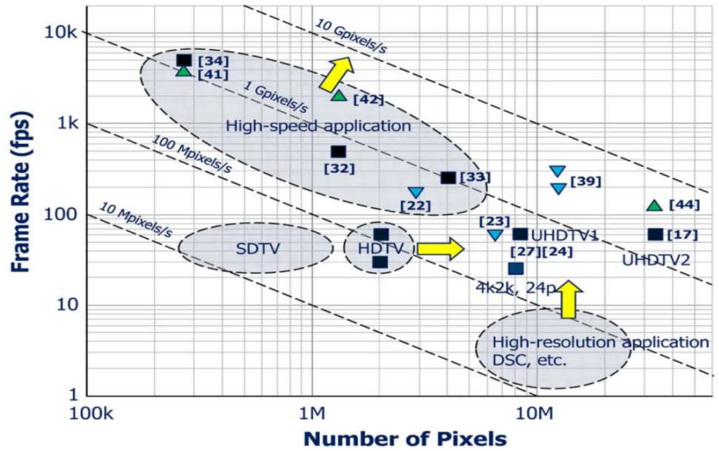






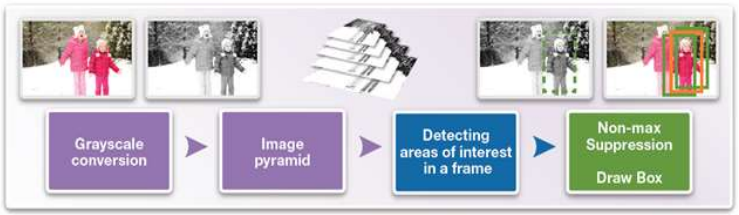
Source: i) OmniVision; ii) ChipWorks; iii) Sony

Larger Sensor Formats and Speed



Source: I. Takayanagi and J. Nakamura,

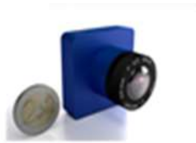
Embedding of image Analysis and Vision Tasks at the Sensor



Pipeline for pedestrian detection

Source: SYNOPSIS white paper on embedded vision

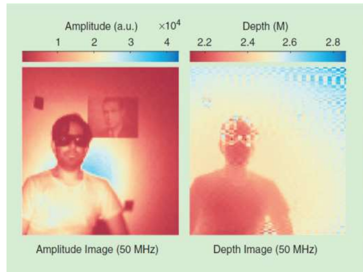
Source: AnaFocus Eye-RIS

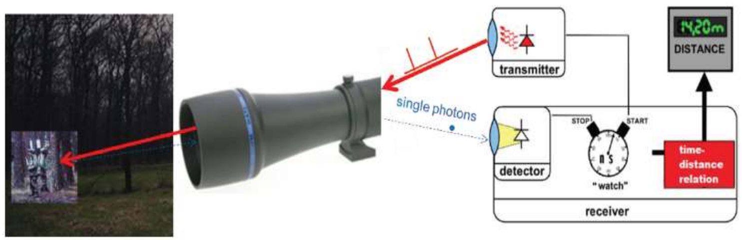


EYE-RIS VSoC

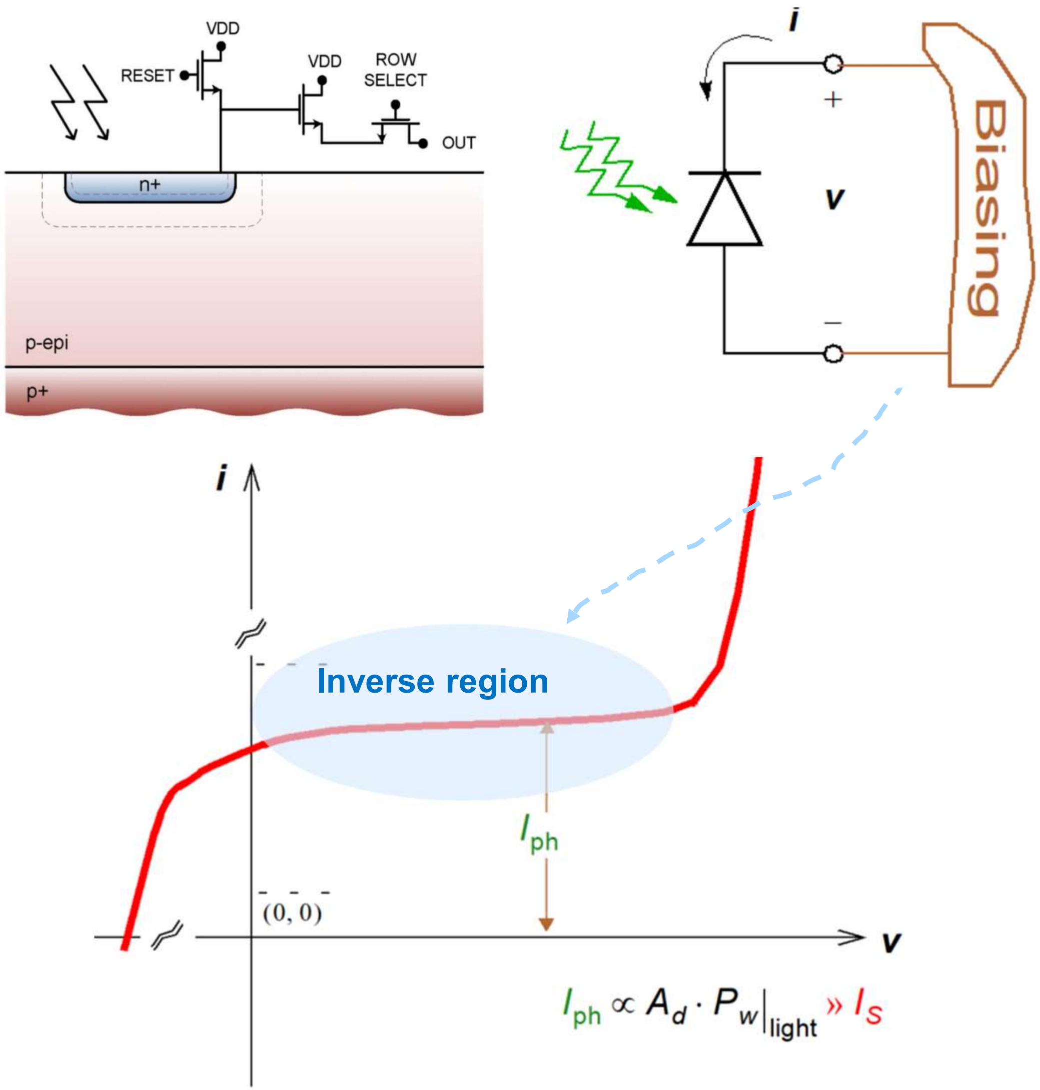
Range Estimation and Combined 2D/3D Imaging

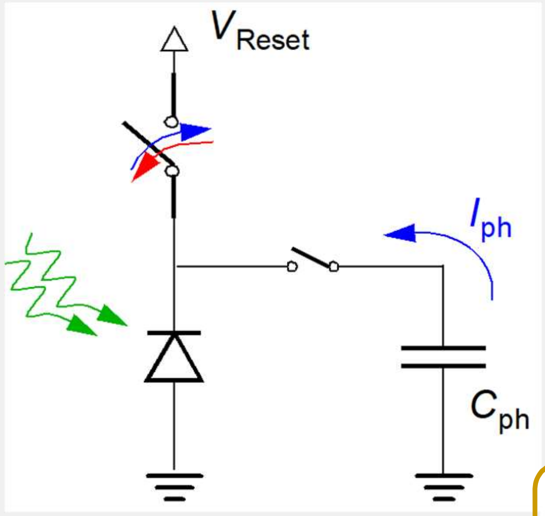
Source: A. Bhandari and R. Raskar





LIGHT-TO-ELECTRICAL TRANSDUCTION IN CMOS: *Integration Mode*





$$V_{ph} = V_{Reset} - \frac{I_{ph}}{C_{ph}} T_{expos}$$

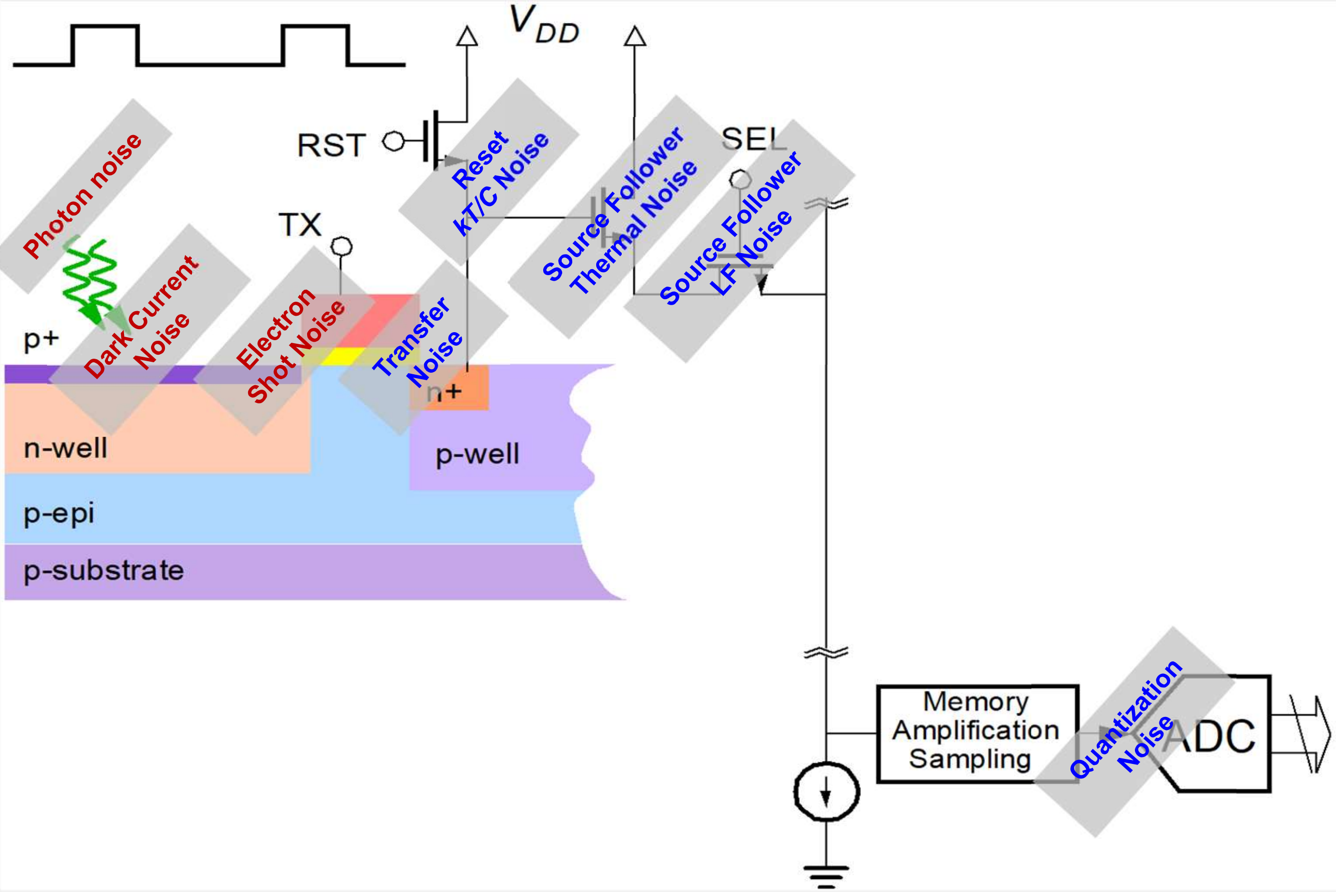
- **Signal power controlled by:**
  - **Photo-current, I_{ph}**
  - **Integration time, T_{expos}**
- **No Intrinsic Gain**

  Photocurrent power is only a fraction of light power
- **No timing information available**

NOISE SOURCES IN *Integration Mode CISs*

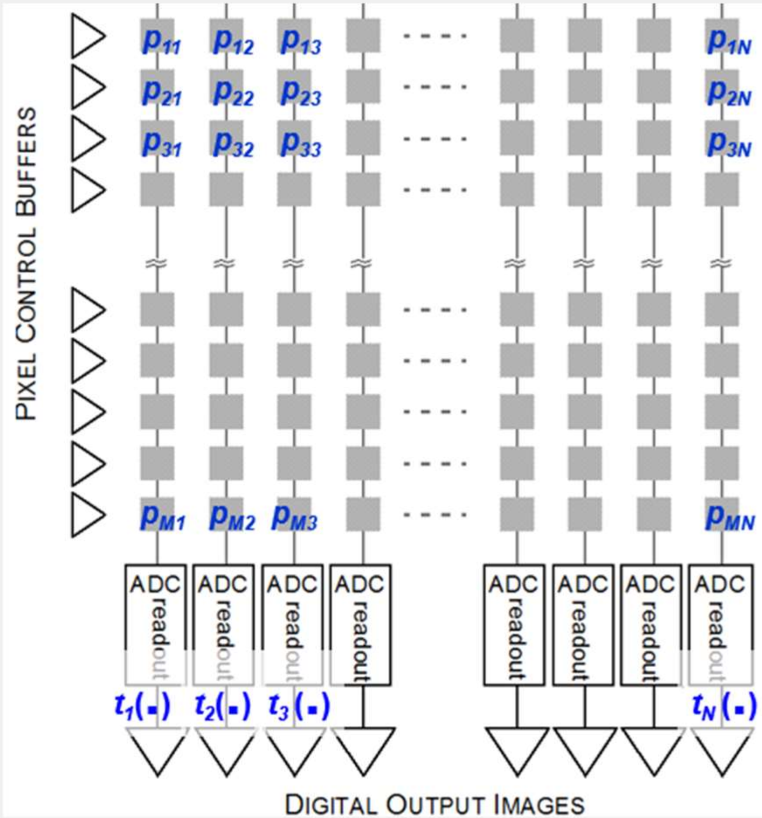
TEMPORAL NOISE

- Microscopic fluctuations produce time-varying random errors in pixel voltages and currents
- Can be only partially corrected: *CDS, CMS*



SPATIAL NOISE

- Caused mostly by mismatches that produce Fixed Pattern Noise
- Can be corrected through calibration



Low Noise CISs: *Illustrative Example*

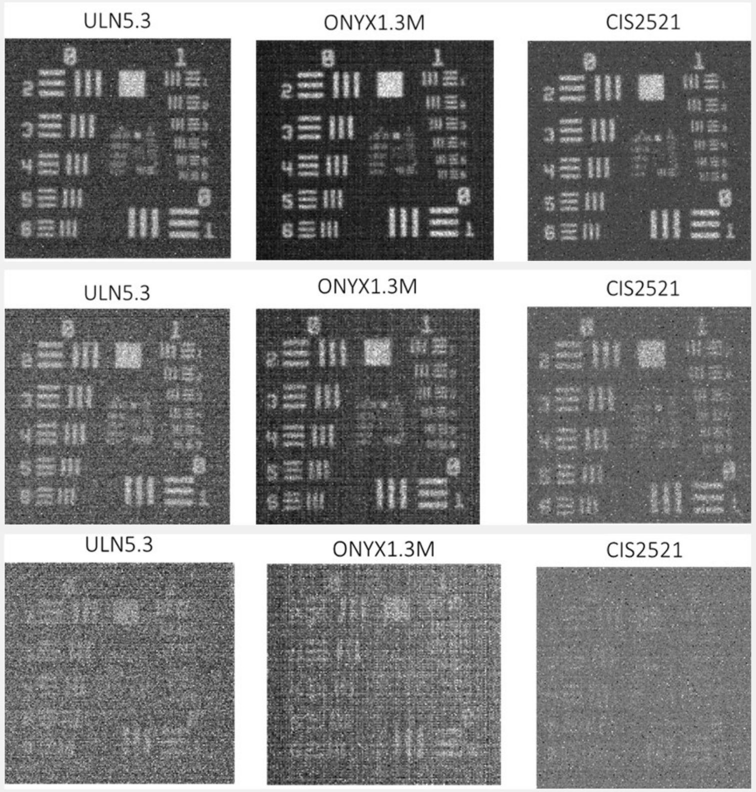
Teledyne-AnaFocus ULN5.3

- **Images at different light conditions and integration time 1/60 s**

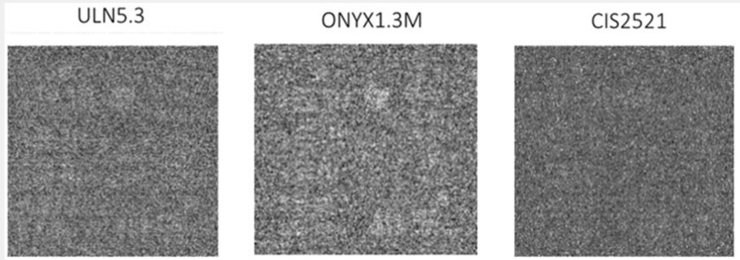
Night level 2 with 10 mlux at F#1

Night level 3 with 5 mlux at F#1

Night level 4 with 1.5 mlux at F#1



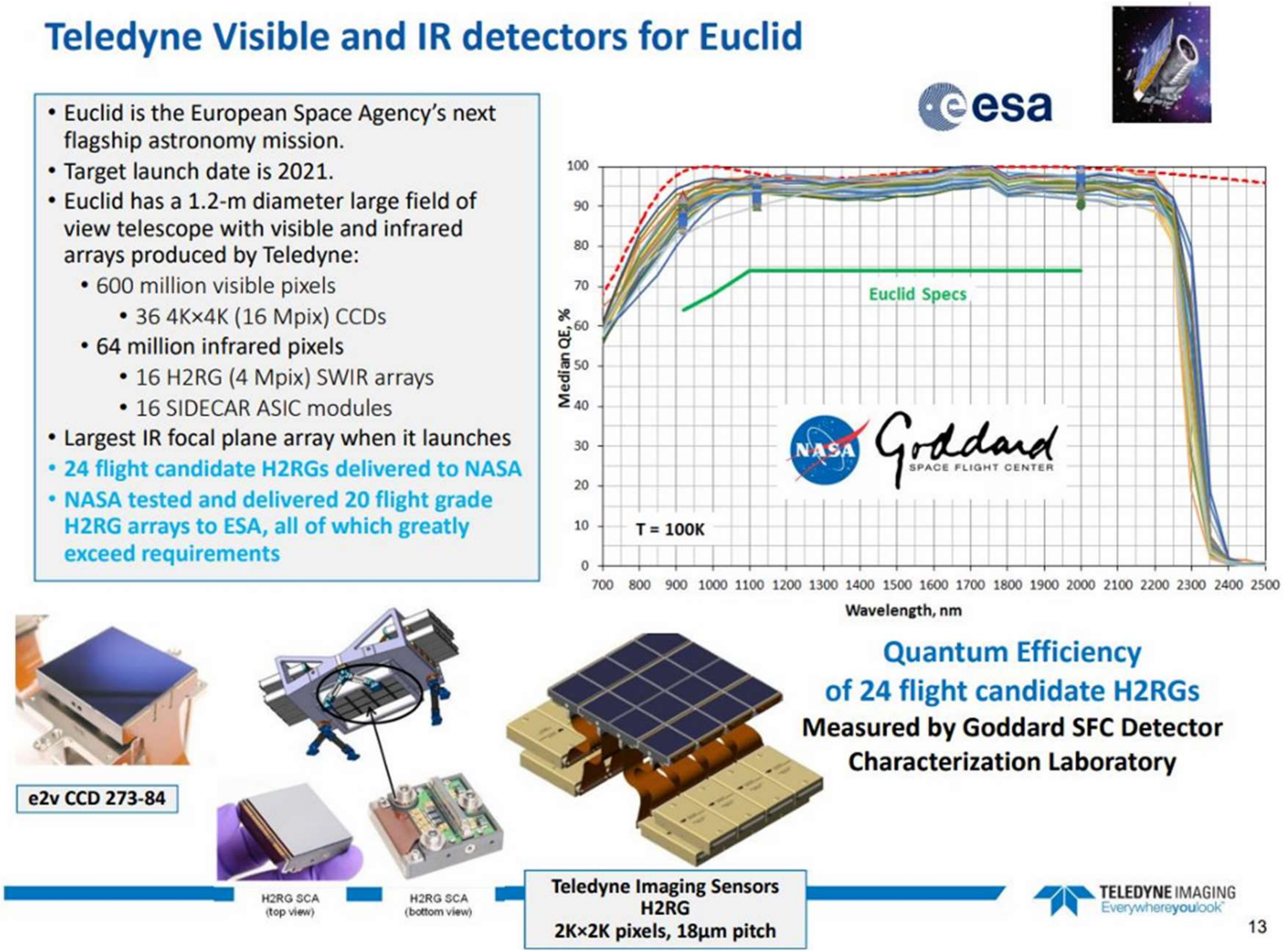
Night level 5 with 0.69 mlux at F#1



- **ULN5.3 achieves higher image quality than CIS2521 using the same pixel pitch**
- **ULN5.3 has similar image quality to ONYX1.3M using a smaller pixel**
- **Readout architecture and the pixel optimization conceived for ULN5.3 permit downscaling the pitch x0.56 without degrading performance**
- **Indeed, ULN5.3 has better noise behaviour than ONYX1.3M**

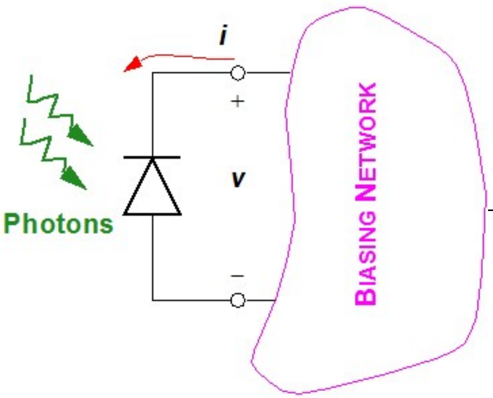
Designation	Night Level 1	Night Level 2	Night Level 3	Night Level 4	Night Level 5
Light source	Full moon 	Half moon 	Partial moon 	Clear Starlight 	Overcast Starlight 
IlluminationRange	40-1000 mlux	10-40 mlux	2-10 mlux	0.7-2 mlux	0-0.7 mlux

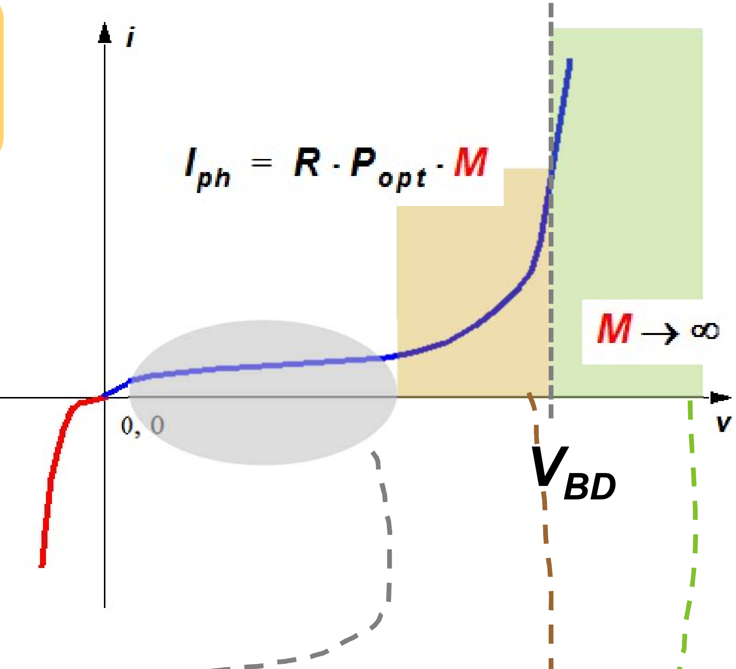
REFERENCE TARGET FOR SPAD-BASED ARRAY SENSORS



LIGHT-TO-ELECTRICAL TRANSDUCTION IN CMOS: *Avalanche Mode*

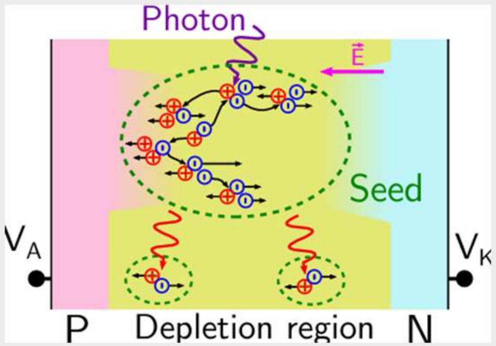
Photodiodes can be **biased** at different **regions** with **different gains** !!

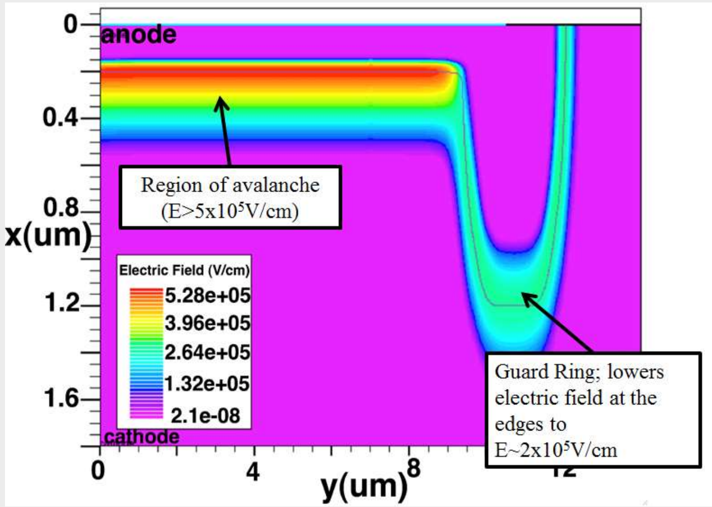




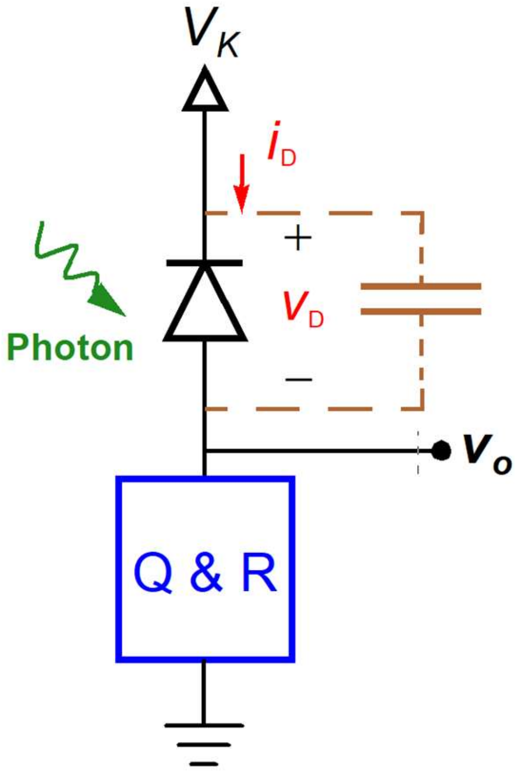
- **INVERSE REGION:** # photo-charges < #photons
  - No Intrinsic Gain
- **AVALANCHE REGION:** #photo-charges > #photons
  - Intrinsic Gain
    - Linear, Incremental Mode
    - Geiger Mode

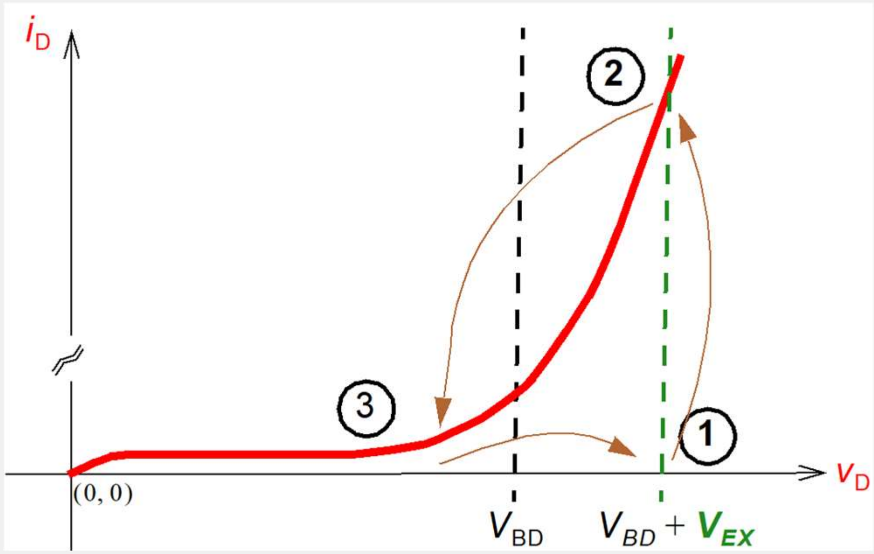
Avalanche behaviors must be carefully assessed using dedicated Technology evaluation CAD (TCAD) tools !!





AVALANCHE PHOTODIODES: Operation Sequence in Geiger Mode





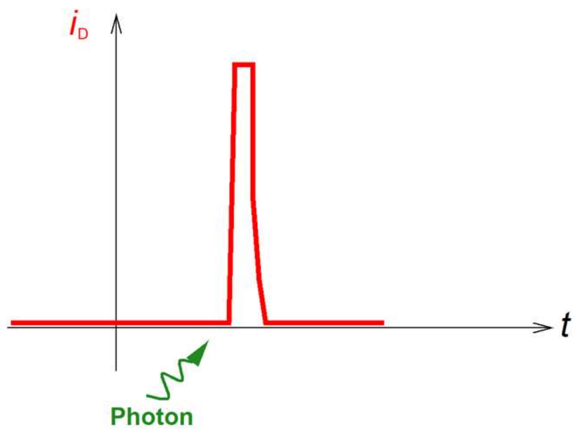
① **Biasing above breakdown:** V_{EX}

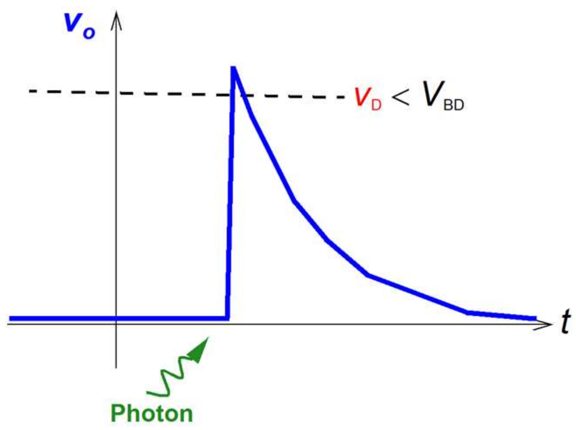
② **Avalanche triggering by single photon events**

③ **Avalanche quenching:**

- **Passive quenching**
- **Active quenching**

① **Recharge to original bias conditions**





Source: M. Sze and K.K Ng, *PHYSICS OF SEMICONDUCTOR DEVICES, John Wiley & Sons 2007.*
IMSE CIS-CVIS Lab, "Characterization-Based Modeling of Retriggering and After-pulsing for Passively Quenched CMOS SPADs". *IEEE SENSORS JOURNAL*, VOL. 19, JULY 2019.

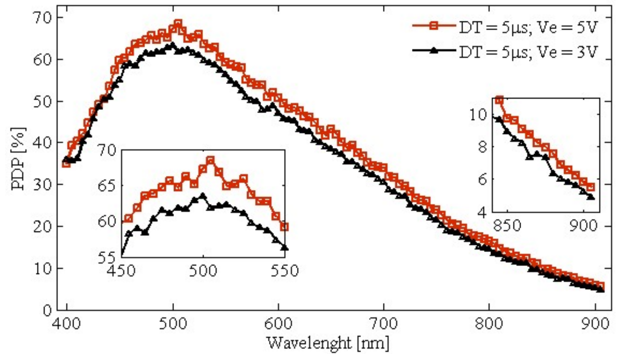
AVALANCHE PHOTODIODES: *Some Relevant SPAD Metrics*

DEAD TIME

- Minimum time between consecutive, detectable photons

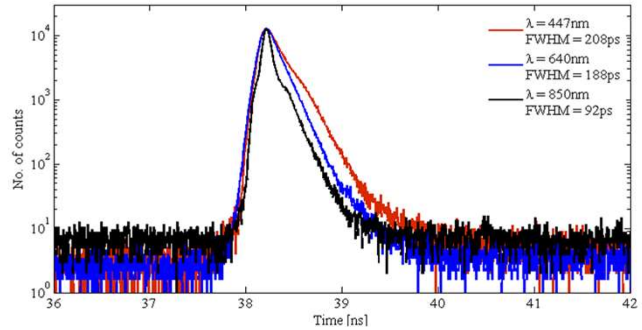
PHOTO DETECTION EFFICIENCY

- Percentage on the impinging photons that are detected and produce avalanches
- Depends on the Photo Detection Probability and the Avalanche probability
- Largely dependent on wavelength and the excess voltage



NOISE SOURCES

- DARK COUNT RATE (DCR) due to thermal carrier generation, tunneling, etc.
- AFTER-PULSING (AP) due to carrier trapping, etc.
- CROSSTALK in SPAD arrays due to diffusion from adjacent locations, etc.

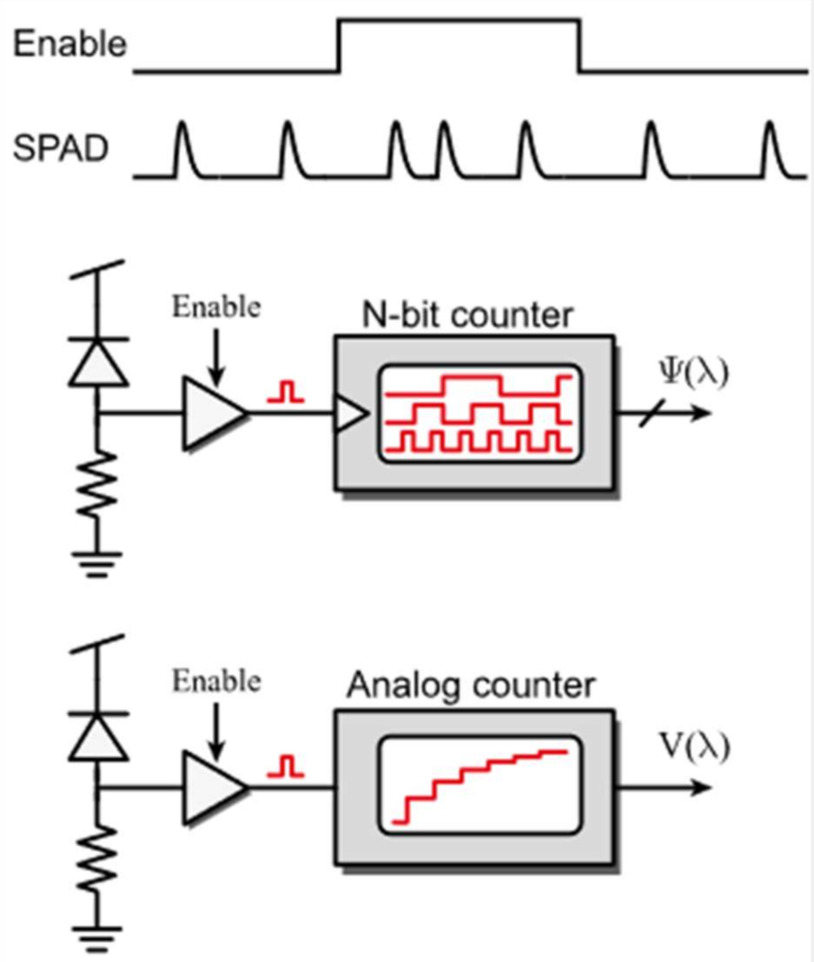


TIME RESOLUTION

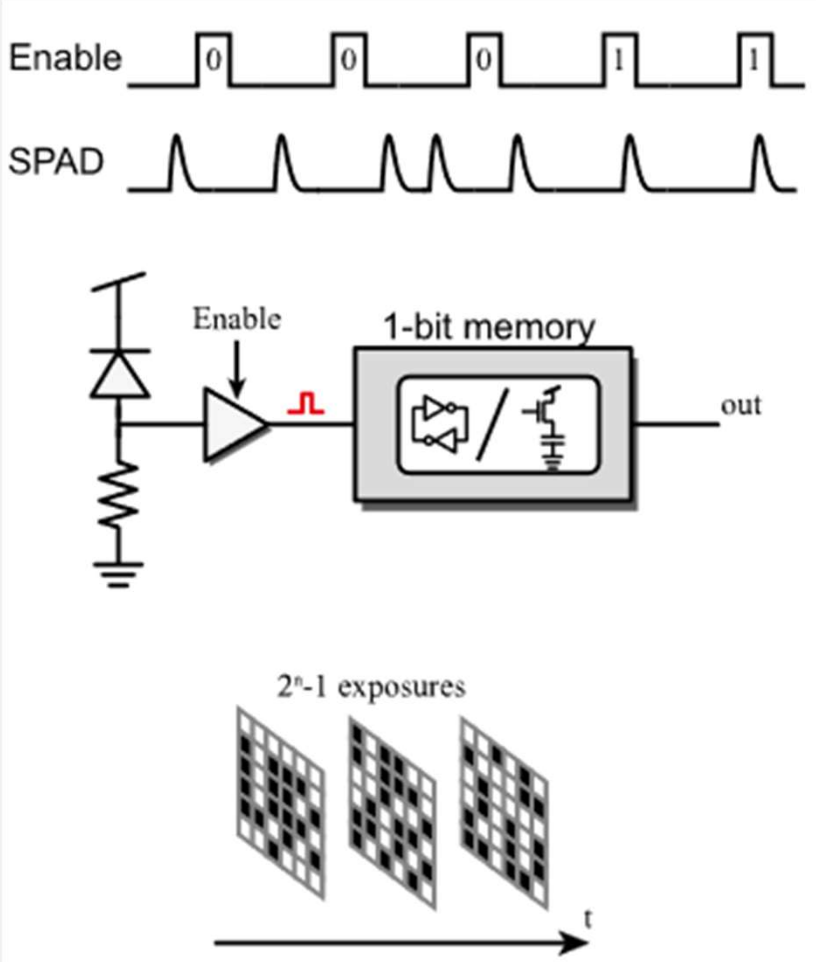
- Characterizes the accuracy/precision in time stamping photo arrivals
- Limited by the procedure employed to measure the time instances of avalanches
- Limited by the delays attainable in the technology
- Limited by time uncertainty - JITTER

SPADs Sensor Functions: Photon Counting and 2D Imaging

Photon Counting



Quanta Imaging

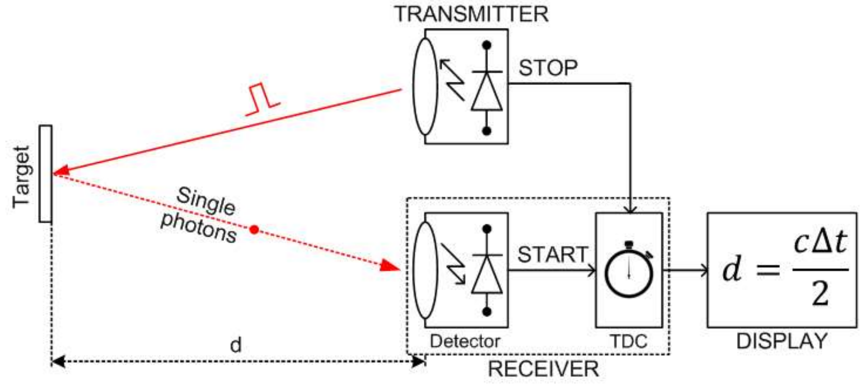


Source: E. Fossum et al., "The Quanta Image Sensors: Every Photon Counts," Sensors MDPI, Vol. 16, 1260, August 2016.

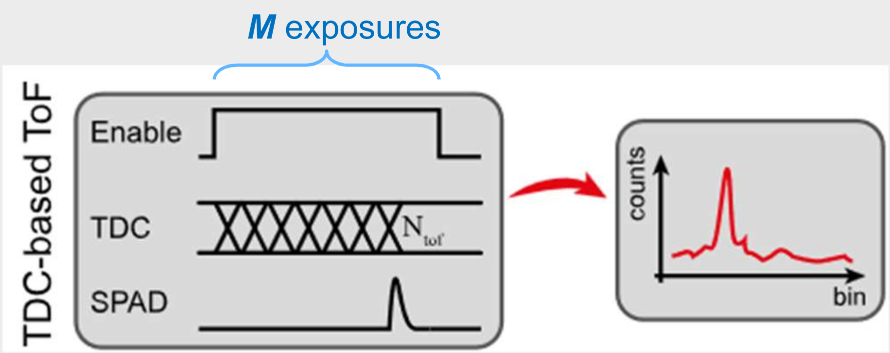
SPADs Sensor Functions: Time-of-Flight - II

Direct Time of Flight concept:

- **Light (laser) emission**
- **Light reflection by the object of interest (target)**
- **Reception of the reflected light and time signalling by the SPAD**
- **Calculation of the distance to the target taking into account the speed of light**

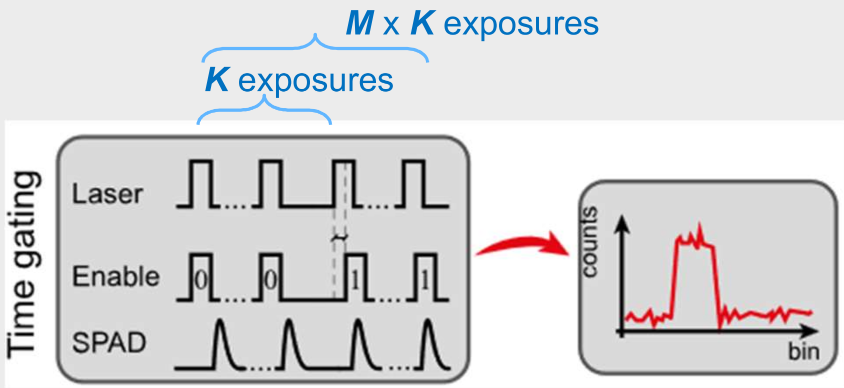


Time Measurement through TDC (Time-to-Digital Converter)



- ☹ **Power-hungry**
- ☹ **Large pixel pitch**
- ☺ **Good resolution**
- ☺ **Fast**

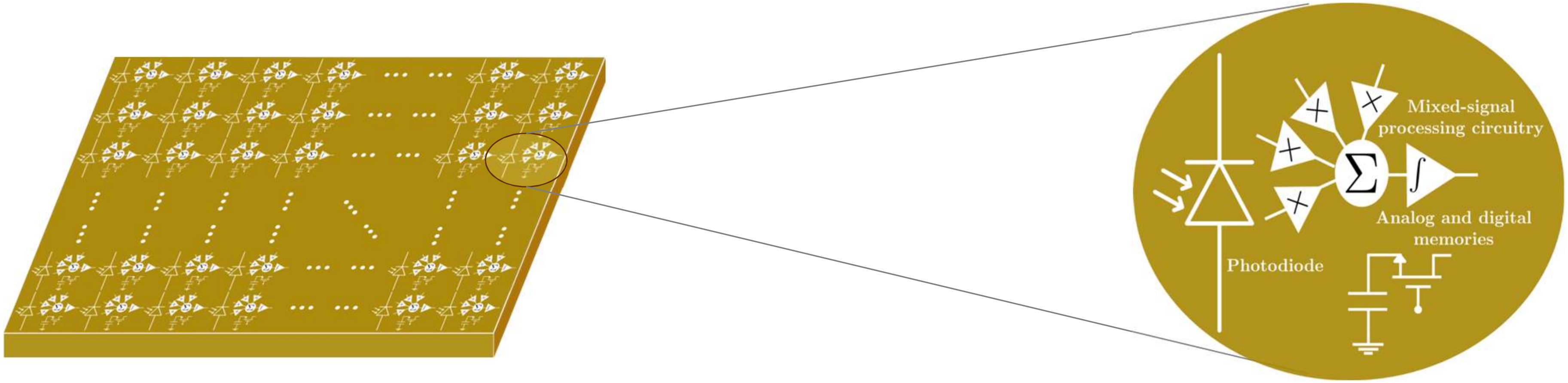
Time Measurement through Time Gating



- ☺ **Background light rejection rejection**
- ☺ **Small pixel pitch**
- ☹ **Worse temporal resolution**
- ☹ **More exposures**

PLANAR VS 3-D STACKED MULTI-FUNCTIONAL PIXEL SENSORS

There are TRADE-OFFS inherent to allocating sensing devices and processing/control circuitry in a shared silicon substrate, as it happens in planar technologies

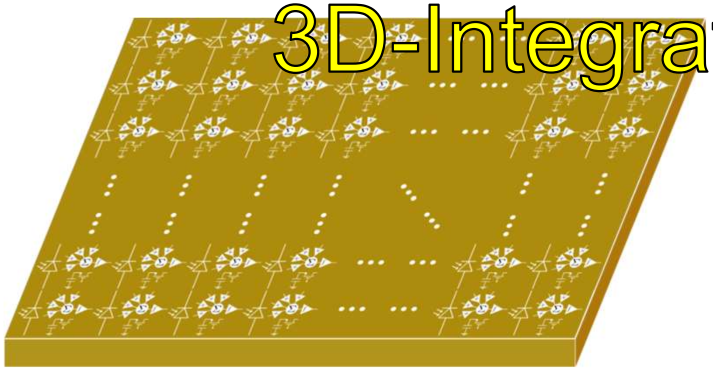


↑ Sensing area ⚖ ↓ Processing area	↑ Processing area ⚖ ↓ Sensing area
☺ Fill factor ↑	☹ Fill factor ↓
☺ Sensitivity to light ↑	☹ Sensitivity to light ↓
☺ Image resolution ↑	☹ Image resolution ↓
☹ Built-in intelligence ↓	☺ Built-in intelligence ↑

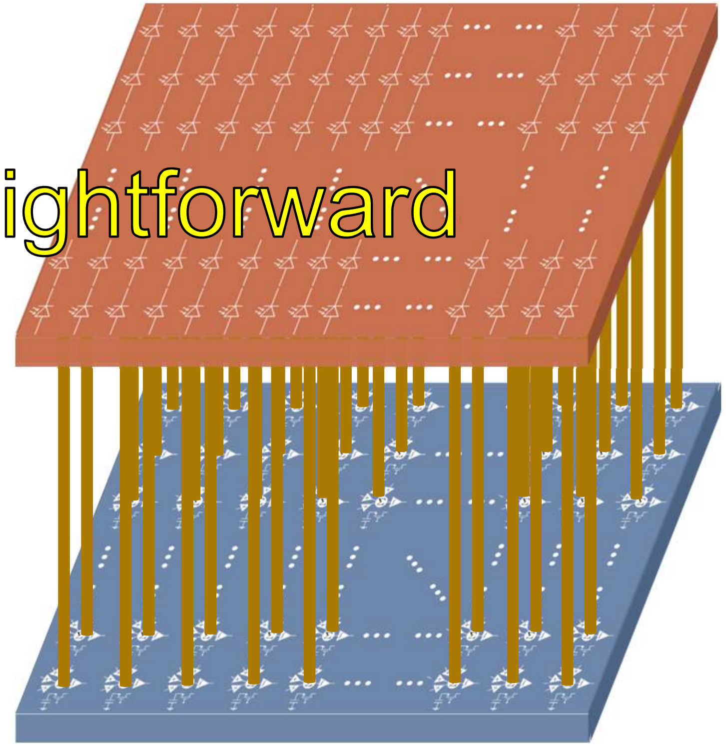
PLANAR VS. 3-D STACKED FPAP-CVIS

TRADE-OFFS can be relaxed by resorting to 3D stacking

- ☺ **Fill Factor** ↑
- ☺ **Sensitivity to Light** ↑
- ☺ **Image Resolution** ↑



3D-Integration is not Straightforward



- ☺ **Built-in Intelligence** ↑

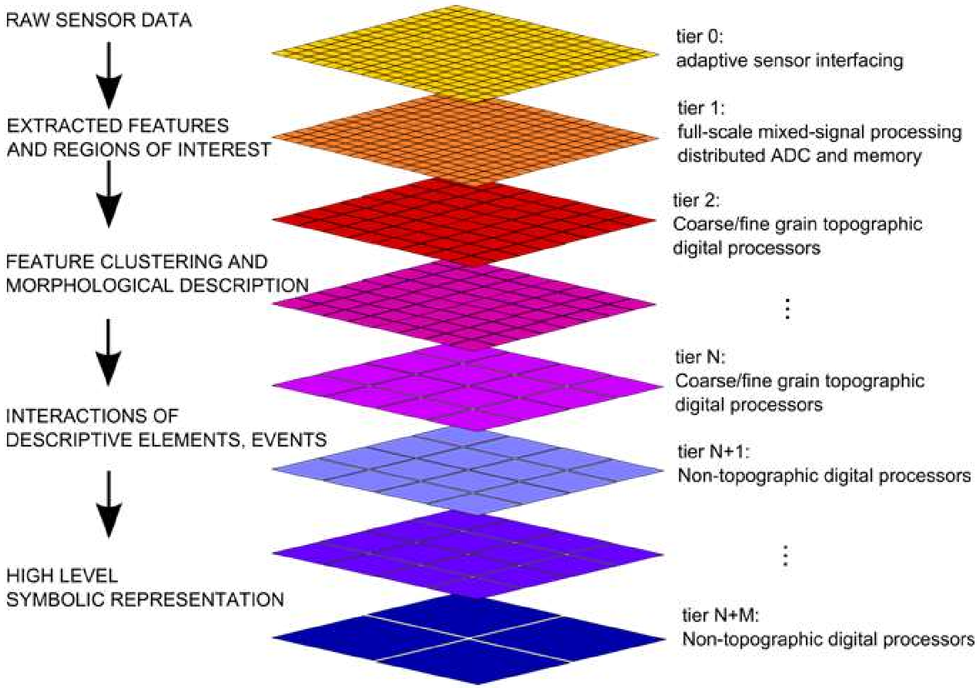
Source: IMSE CIS-CVIS Lab, "CMOS-3D Smart Imager Architectures for Feature Detection". *IEEE J. Emerging Select. Topics Circuits Syst.*, Vol. 2, pp 723-729, 2012.

3-D STACKING: A KEY INGREDIENT FOR SMART CISs

Pentagon Contract Goes to Irvine Sensors:

***Los Angeles Times*, 1991**

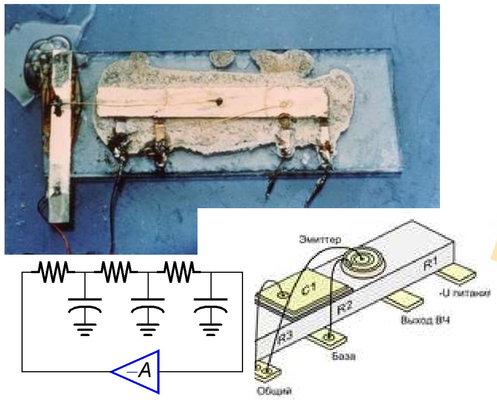
Pentagon Contract Goes to Irvine Sensors: Irvine Sensors Corp., a Costa Mesa firm developing a technology to stack computer chips in a package the size of a sugar cube, said Tuesday that it has won a $500,000 contract from the Army to develop technology for a new class of missile warning sensors.



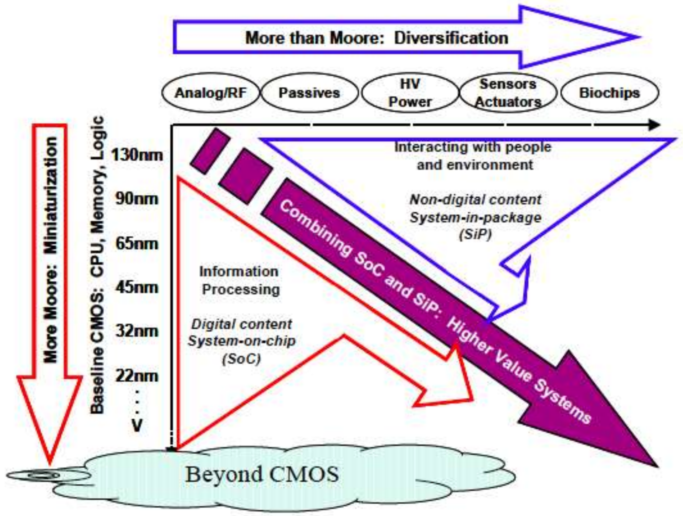
- **IMAGE RESOLUTION:** Minimum amount of data required for processing ?
- **PROCESSING CAPABILITIES:**
  - processing primitives ↑ elementary cell area ↑ processor grain ↓
  - Local storage !?
  - Power consumption !?
  - Resilience !?
- **PROCESSING PRIMITIVES:**
  - Programmable spatial filtering ?
  - Image enhancement ?
  - Edge detection ?
  - Local extrema detector ?
  - etc. ?
- **SENSOR-TO-PROCESSOR MAPPING:**
  - Raw subsampling ?
  - Compressed sensing ?
  - Binning ?
  - etc. ?

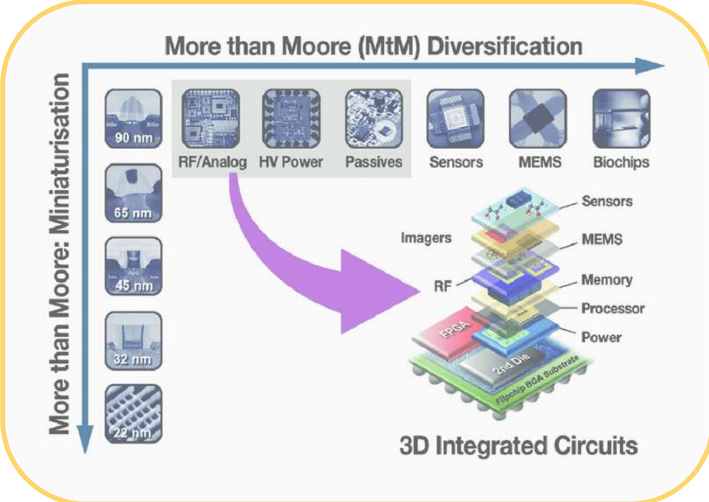
MICRO-TECHNOLOGIES TREND FROM CIRCUITS TO AUTONOMOUS MICROSYSTEMS

1958



2005

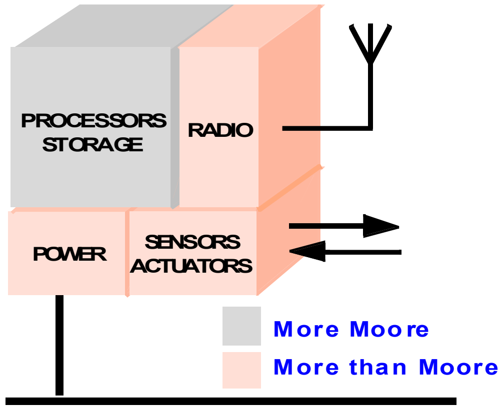




SOME SIGNIFICANT INGREDIENTS

- Transistor Scaling (Moore´s Law)
- Multi-Core Von Neumann Processors
- MEMs and Heterogeneous Integration
- 3D Stacking
- Energy Harvesting
- Non-conventional processing paradigms and AI

. . . . etc.

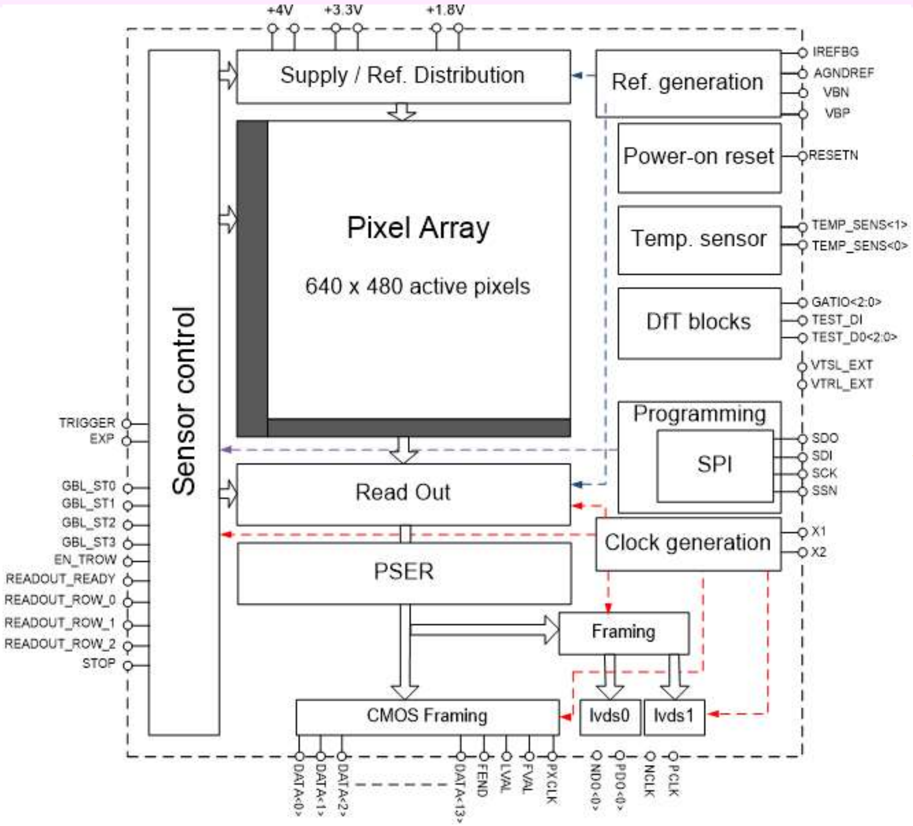


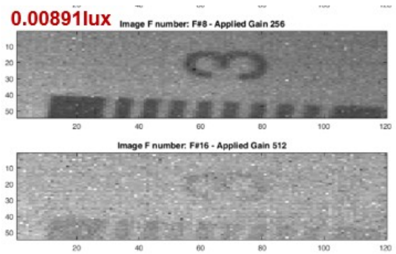
Source: P. Saffo, *INSTITUTE FOR THE FUTURE, Memlo Park California*
https://irds.ieee.org/ *INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS* ™
Wikipedia – *THE FREE ENCYCLOPEDIA*

EXAMPLES OF 3-D STACKED SMART CISS: Low-Noise CIS

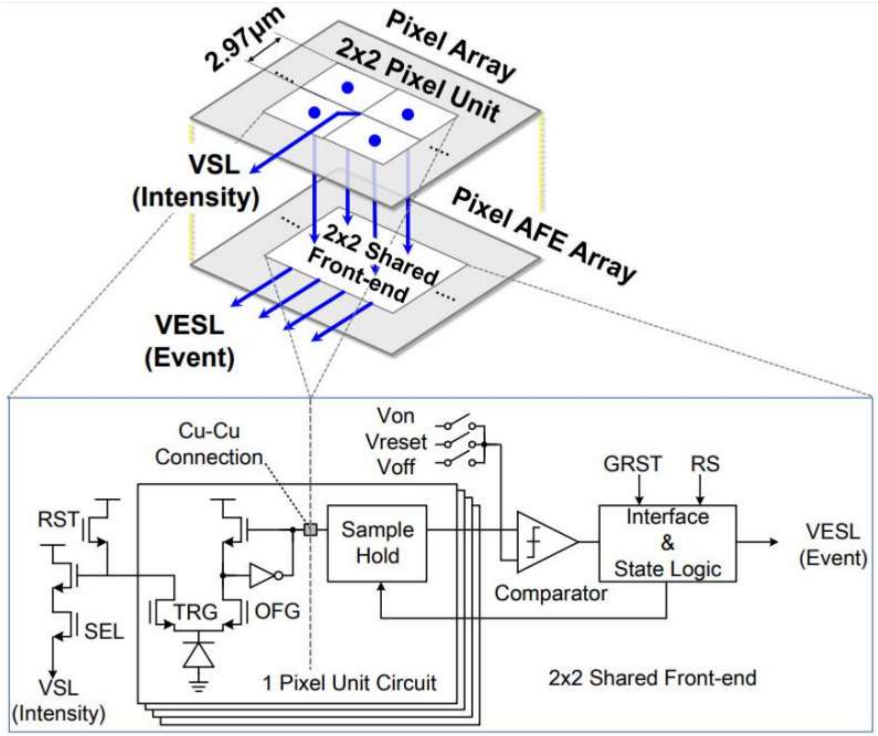
TELEDYNE ANAFOCUS Everywhereyoulook

LOW-NOISE CIS AND TRANSITION FROM PLANAR TO 3-D STACKING TECHNOLOGY

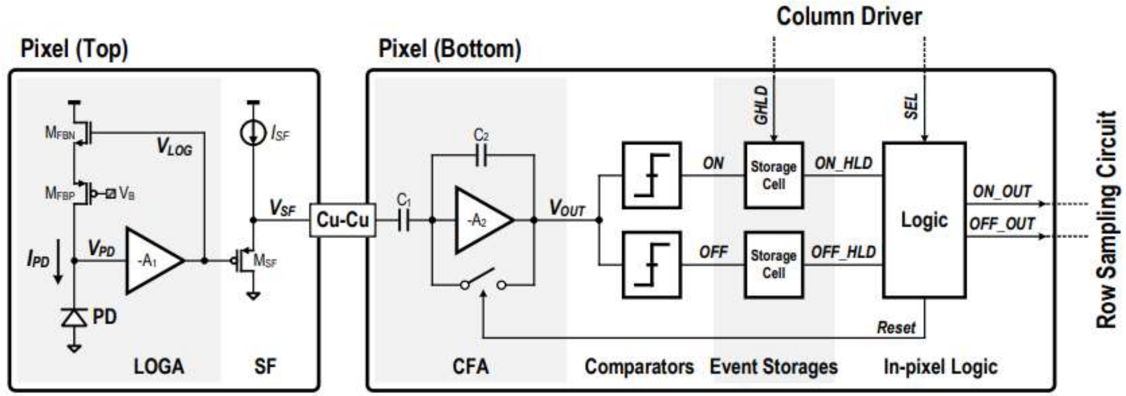




EXAMPLES OF 3-D STACKED SMART CISs: Low-Noise CIS



⚠ **Coming back to synchronous systems!**



SONY

SAMSUNG

Source: A. Niwa et al., "A 2.97um-Pitch Event-Based Vision Sensor with Shared Pixel Front-End Circuitry and Low-Noise Intensity Readout Mode." *ISSCC FEB. 2023.*
Y. Suh et al., "A 1280x960 Dynamic Vision Sensor with a 4,95um Pixel Pitch and Motion Artifact Minimization." 2020 *IEEE INTERNATIONAL SYMPOSIUM ON CIRCUITS AND SYSTEMS (ISCAS)*, 2020.

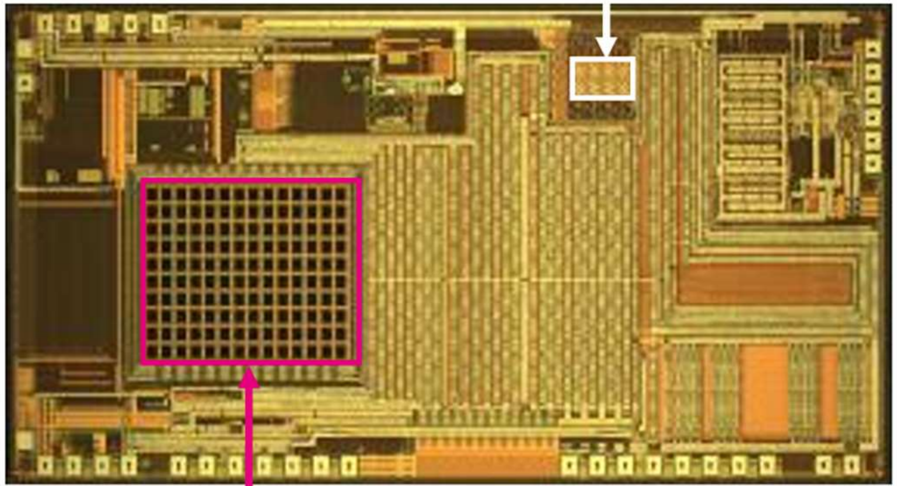
ST VL53L5: Silicon Description

VL53L5 specific silicon functionalities:

VCSEL Driver

Return and reference SPAD arrays

16 histogram parallel Readouts (64 obtained by scanning by 4)



Microcontroller

Full histogram processing

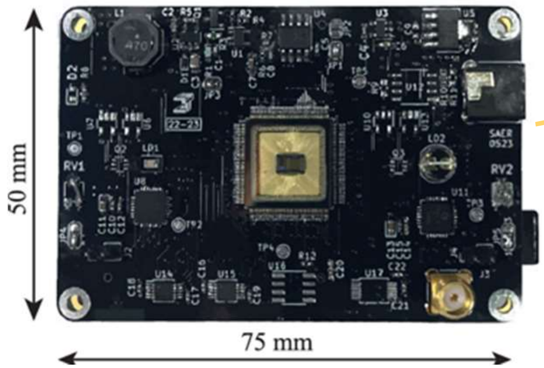
Autonomous ranging specific management

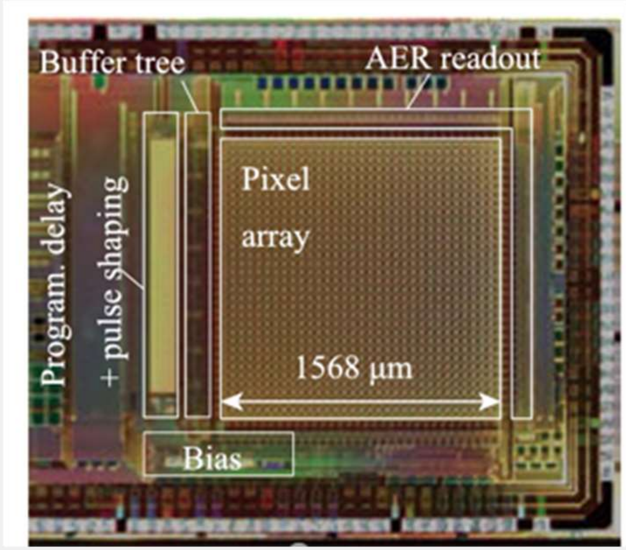
Source: Sara Pellegrini, *FROM CIRCUITS TO SENSORS*. AIDinnova Course at CERN.

EXAMPLES OF COMMERCIAL SPAD ARRAYS

©Sara Pellegrini @ ST MICROELECTRONICS

PROJECT PREDECESSORS: *Betelgeuse Diameter Measurements with SPADs*





EXPERIMENT

- Measurement of Betelgeuse´s diameter of while occulted by the asteroid Leona during the night of 12 December 2023

CMOS SPAD ARRAY SENSOR

- 64 x 64 event-based sensor array in 110 nm
- Time-gating measurement
- 24.5 µm pitch
- 3.5 % fill factor
- ~25 psec jitter

Source: IMSE CIS-CVIS Lab, “Dynamic Vision With Single Photon Detectors: A Discrete DVS Architecture Using Asynchronous Sensor Front-Ends.” *IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS*, 2025

SOME PROJECT TARGETS AND CHALLENGES AND STATE-OF-THE-ART PROGRESS

- Gran formato (> 2000 x 2000 píxeles; 1 píxel = 20 micras), lo que implica una gran área por chip.
- Tecnología apilada en 3D para alcanzar un factor de llenado de cada píxel cercano al 100% (superior al 95%) sin uso de microlentes. El factor de llenado es el porcentaje del área total del píxel que es sensible a la luz.
  - Utilización de técnicas de *Backside Illumination* (BSI)
  - Integración vertical a nivel de obleas:
    - sensores y
    - circuitería de control y lectura de los SPADs
- Alta eficiencia de detección de fotones en un amplio rango espectral en el rango visible: 30% a 350 nm, 80% a 550 nm, 30% a 900 nm.
- Resolución temporal inferior a 30 picosegundos.
- Tasas mínimas de corriente de oscuridad[10]

Además, para mejorar la resolución temporal y permitir realizar interferometría de intensidad en el visible con varios telescopios, serían necesarias dos funcionalidades específicas:

- Decimación de datos[11] y
- Asignación de una marca de tiempo a cada píxel.

- **The sensor as it is not available in the existing art**
- **Many of the specs are far away from the current existing art**
- **Some specs may be close to physical limits**

TECHNOLOGY CHALLENGES

- **Stitching technique will be needed due to the large format**
- **Three stacked layers may be needed:**
  - **Light sensitive Tier for sensing devices**
  - **Pixel circuitry Tier for SPAD Control and readout**
  - **Processing Tier for data processing and feedback control**

SPAD SENSOR CHALLENGES

- **Extensive and intensive iteration cycles needed:**

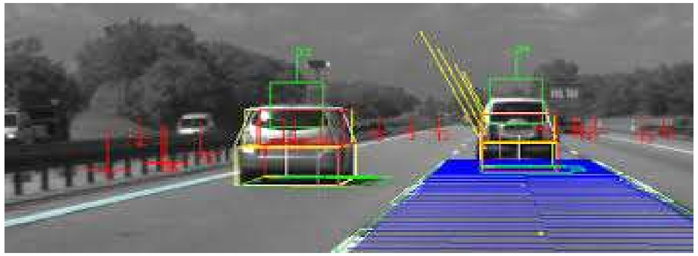
  TCAD simulations → Technology tuning → Pixel design → Electro-Optical Characterization
- **Peak PDEs may be close to physical limits**
- **Spectral PDE uniformity at low and high wavelengths require involved device engineering**

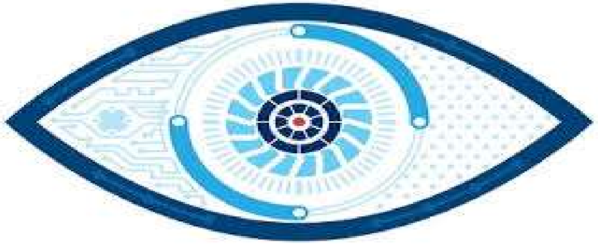
SPAD PIXEL CIRCUITRY

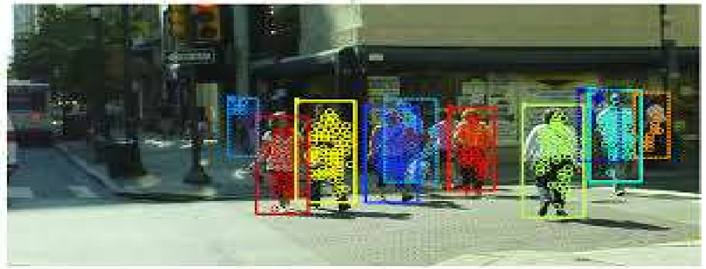
- **TDCs needed for the required time resolution**
- **Large sensitive area may compromise Jitter**

POST PROCESSING

- **Supervisory functions require innovative processing**







Thanks a Lot for Your Attention !!